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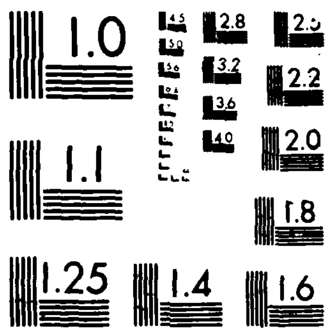
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COMPARISON OF DROP-SIZE MEASUREMENTS FOR SIMILAR ATOMIZERS

SPECIAL REPORT
No. SwRI-8858/2

By

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San Antonio, TX

in cooperation with some members and associates of
ASTM Subcommittee E29.04 for
Liquid Particle Size Measurements

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The performance of 17 drop-size measuring instruments including six different types were compared for two types of standard sprays. Ten instruments were compared on one type of spray, and eleven on the other, with some instruments being used on both types. A number of nominally identical atomizers were tested at different laboratories using drop-sizing instrumentation. These tests followed a set of well-defined test conditions and measurement locations as defined by a committee of test participants. The results indicated systematic differences in instrument performance beyond what could be attributed to problems in spray reproducibility. Differences in average drop size were as large as a factor of five. However, good to excellent agreement was observed between observations for some types of instruments.

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FOREWORD

This report documents results of comparative spray measurements at a number of different laboratories. These tests were conducted on a voluntary basis, and test results were provided without charge to Southwest Research Institute (SwRI) which acted as the control laboratory. SwRI provided funds for coordinating the tests, data analyses, and presentation of the results. However, the procedures used to reduce the data were developed under sponsorship of the Office of Naval Research (ONR) under contract N0001485-C-0841, with technical monitor Dr. Richard S. Miller. In order to archive these results in the Defense Technical Information System (DTIS), these results are presented in the form of an ONR report.

ACKNOWLEDGEMENTS

This work was produced as a result of labors by many. These tests were an unofficial effort of ASTM Subcommittee E29.04, Liquid Particle Size Measurements, chairman Dr. Julian M. Tishkoff. The "in-house" editorial board for this report included the following members of Subcommittee E29.04: Dr. Robert D. Ingebo, NASA Lewis Research Center; Dr. Charles A. Martin, Parker Hannifin Corp; Dr. Rolf D. Reitz, General Motors Research Laboratories; Mr. James Sager, Ex-Cell-O Corp.; and Dr. V.E. Dietrich, Spraying Systems Co. Funding for coordinating the spray tests and producing this report was provided by Southwest Research Institute (SwRI). Funding for developing some of the data analysis techniques and for performing spray tests at SwRI was provided by the Office of Naval Research through technical monitor Dr. Richard S. Miller. Mr. Blake Stapper, Ms. Deborah J. Rhodes, and Ms. Shirley Hoover were all significantly involved in manuscript preparation. Finally, this report is the result of tests conducted by a number of people including: Dr. David Mahler, KLD Associate; Dr. Rolf D. Reitz, General Motors Research Laboratories; Dr. Roger W. Tate, Delavan Inc; Mr. Barry Weiss, Parker Hannifin Corp.; Mr. John Fury, Spraying Systems Co.; Professor W.E. Yates, University of California, Davis; Mr. Richard Huddas, Ex-Cell-O Corp.; Dr. William Bachalo, Aerometrics Inc.; Mr. Jan B. Kennedy, United Technologies Research Center; Professor Norman A. Chigier, Carnegie Mellon University; Mr. John R. Oldenburg, NASA Lewis Research Center; Dr. Manfred Aigner, Universitat Karlsruhe; Mr. Randall C. Williams, Garrett Turbine Engine Co.; Mr. Thomas A. Bassett, Bete Fog Nozzle Inc.; and Ms. Deborah J. Rhodes, Southwest Research Institute.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The measurement of drop size is necessary in a wide number of applications including, fuel sprays for combustion, agricultural sprays, spray painting, spray drying processes, cooling purposes, meteorology, and aircraft icing. Since many processes depend critically on the average drop size and size distribution, accurate measurement of these parameters is very important. Various instruments are available which measure drop-size characteristics, but there is concern that the results of these measurements may not be reproducible for instruments of different design, or even among different instruments of the same design.

Comparison of the performance of various drop-sizing instruments on the "same" spray have been reported by Olsen et al. (1), Simmons and Harding (2), Hammond (3), Jackson and Samuelsen (4,5), and Dodge et al. (6). These comparisons have been limited to two or three types of instruments.

The purpose of this report is to document the results of an extensive set of tests involving measurements at 15 laboratories using a total of 17 different instruments. The 17 instruments included six different types, so that comparisons between instruments of the same design, as well as comparisons between instruments using completely different physical principles, could be made.

This report is organized as follows. The protocol for performing the spray drop-sizing tests is defined. The instruments which were used to test the atomizers are identified in terms of manufacturer and model number. Participating laboratories are identified only by a code letter. The results are presented in graphical form, and a statistical summary is presented. The complete data are presented in Appendix A. A summary of these results have been submitted for publication (7).

The discussion of the results is purposely limited to avoid an implied endorsement of any instruments. Therefore, the reader must make his own judgments regarding the results. The drop-sizing instruments identified in this report were those used by participants who volunteered for these tests; they do not represent a complete sample of all available types or an endorsement of those used.

Southwest Research Institute (SwRI) acted as the control laboratory and was responsible for coordinating the tests, reducing the data, and presenting the results. The test procedure evolved from a committee made up of test participants (see Acknowledgments).

DESCRIPTION OF SPRAY TESTS

Test Procedure

In order to satisfy the diverse requirements of the test participants, two different classes of atomizers were tested. One design was a moderate capacity pressure-swirl atomizer tested on water. The second was a smaller capacity pressure-swirl atomizer tested with aircraft fuel system calibration fluid, MIL-C-7024 Type II. The larger capacity design was a Delavan WDB solid-cone, simplex swirl atomizer with a flow number of 2.26×10^{-5} kg/s Pa (14.9 lbm/hr psid) and a nominal cone angle of 45° for water. The smaller capacity design was a Parker-Hannifin P/N 6780205 hollow-cone, simplex swirl atomizer with a flow number of 2.05×10^{-6} kg/s Pa (1.35 lbm/hr psid) and a nominal cone angle of 80° for aircraft fuel system calibration fluid. In the tables in this report the Delavan atomizer is identified as DLN and the Parker-Hannifin atomizer as P/H. The Delavan atomizer was tested using 10 drop-sizing instruments and the Parker-Hannifin atomizer using 11 instruments.

Based on traditional practice in different industries, the Delavan atomizer was tested at an axial distance of 152 mm (6 in), while the Parker-Hannifin atomizer was tested at an axial distance of 51 mm (2 in). The optimum test point in the spray varies with instrument design, and these were compromise locations. Measurements at the centerline and edge of the spray were required, and measurements at various radial distances from the centerline of the spray to the edge were optional. For line-of-sight integrating instruments (e.g., laser-diffraction), centerline measurements were actually through the entire spray at the spray centerline (see Figure 1). For the Delavan atomizer, the edge was defined as 63.5 mm (2.5 in) from the centerline (at an axial distance of 152 mm (6 in)), and radial steps of 12.7 mm (0.5 in) were suggested. For the Parker-Hannifin atomizer, the edge was defined as 44.5 mm (1.75 in) from the centerline (at an axial distance of 51 mm (2.0 in)), and radial steps of 6.4 mm (0.25 in) were suggested.

A philosophy of equivalent atomizers was used for the tests reported here in which approximtely 12 atomizers of the same design were tested at the control laboratory and any atomizers showing significant deviation from the others were removed. After removal of one or two atomizers from each group, the spray characteristics for the remaining atomizers as measured at the control laboratory in terms of centerline Sauter mean diameters (D_{32}'s), were as shown in Table 1 for the Parker-Hannifin atomizers and Table 2 for the Delavan atomizers. (See ASTM Standard E799-81 for definition of D_{32}.)

The standard nozzles selected were based on measurements through the spray centerline using a Malvern laser-diffraction instrument at the same conditions as specified in the test procedure. For the Parker-Hannifin atomizers, the standard deviation of the SMD's expressed as a percentage of the mean (coeff. of variation), was 3.0 percent at 345 kPa (50 psid) and 4.7 percent at 689 kPa (100 psid). Note that many of the results presented in this report are expressed as standard deviations normalized by the mean values, and these normalized standard deviations are called coefficients of variation. The maximum spread of SMD's among Parker-Hannifin atomizers actually sent out for testing at other laboratories was 10.6 percent at 345 kPa (50 psid) and 13.8 percent at 689 kPa (100 psid). For the Delavan atomizers, the coefficient of variation of the SMD's was 2.9 percent at a differential pressure of 276 kPa (40 psid) and 2.1 percent at 689 kPa (100 psid). The maximum spread of SMD's among Delavan atomizers actually sent out for testing at other laboratories was 6.8 percent at 276 kPa (40 psid) and 7.0 percent at 689 kPa (100 psid). The differences shown in Tables 1 and 2 were due to instrument precision and test reproducibility in addition to actual variation in atomizer performance. The variation in performance between atomizers was judged to be acceptable for the purposes of the round-robin tests.

The selected atomizers were sent out "in parallel" for simultaneous testing at numerous laboratories. This approach resulted in wide participation over a reasonably short period of time with many state-of-the-art instruments.

The test procedures for the two different atomizer types were defined in such a way as to allow the broadest participation of laboratories and instruments. In some cases they were not the optimum conditions for some instruments. Results of previous

round-robin tests had shown that standard measurement locations and procedures were necessary in order to compare data. Similarly, the results reported here indicated the large differences in spray characteristics at different radial locations within the sprays, necessitating well defined sampling locations.

The test procedures are described in detail elsewhere (8) but are summarized in Table 3. Included in Table 3 are both the recommended conditions and those actually used at the different laboratories. At some laboratories the conditions of the test were outside the recommended ranges, and in some cases they were not reported. Some of the differences between results at different laboratories may be attributable to differences in the spray conditions, which are documented in Table 3. Two other possible sources of differences related to the test procedure are (1) errors in positioning the drop-sizing instrument relative to the atomizer, and (2) differences in the radial profiles of the drop-size distributions for different atomizers.

Also included in Table 3 are the atomizer numbers of atomizers used in the tests at different laboratories which correspond to those listed in Tables 1 and 2. This allows for a correction to be made to the reported data for each laboratory based on the relative atomizer performance as listed in Tables 1 and 2. Such a correction would imply that differences shown in Table 1 and 2 were due to actual atomizer variations rather than test condition repeatability and instrument precision at the control laboratory. Such corrections have not been attempted for the results reported here.

Instrumentation

Tests of the standard sprays were conducted using 17 instruments representing 6 different instrument types and different models within some types. The instruments used at each laboratory are specified in Table 4 as well as the instrument size range, the sampling volume and type, and which atomizers were tested. Dodge (9) has shown that the performance of a Malvern laser-diffraction instrument can be considerably improved if the relative responsivities of the 30 detector elements have been determined and their differences corrected. A shorthand notation used in this report for this procedure is to refer to it as producing a set of custom detector responsivities or a "calibrated" instrument. Hirleman and Dodge (10) have confirmed for a number of Malvern instruments that this procedure improves instrument performance. For that

reason, the Malvern instruments, which represented 9 of the 17 total instruments, were subdivided into two groups of "calibrated" (custom detector responsivities) and "uncalibrated" (standard detector responsivities) units. There were 6 instruments with custom detector responsivities and 3 without, including 2 model 1800's which cannot be calibrated with the procedure.

A complete description of the 6 instrument types listed in Table 4 is beyond the scope of this report. However, a brief description is provided along with references for further information. The nine Malvern instruments listed in Table 4 all operate on the principle of the relative angular scattering intensity for laser-light diffracted in the forward direction near the axis of the system (11-13). Other information regarding the accuracy of these instruments or performance relative to other instruments is provided in Refs. 2-6, 9, 10, 14, and 15. The nine Malvern instruments included two model ST1800's, four 2200's, and three 2600's. The 2600 model is the current (1986) production version.

The four Aerometrics instruments used in these tests were all of a similar type, and operate on the principle of the phase shift as a function of angle for light refracted through the drops in an off-axis forward direction (16,17). Discussions of accuracy and comparisons of the Aerometrics instrument with other measurements are reported in Refs. 4-6.

The three PMS instruments involved in these tests included 2 optical array probes (OAP) and one forward scattering spectrometer probe (FSSP) instrument. One OAP and one FSSP instrument were both used by laboratory C to analyze the sprays, with the results from the two instruments combined for one continuous result. The FSSP was set for a range of 5 to 95 micrometers and the OAP for 21.3 to 1875. micrometers with an overlap region of 20 to 80 micrometers. (These two instruments were counted as one.) The OAP is an optical imaging device in which individual drop images are formed on a diode array and the size is measured by the number of diodes shadowed by the image (18,19). Some reports discussing the accuracy of the OAP instrument may be found in Refs. 20-22. The FSSP is a nonimaging instrument based on forward light scattering intensity (19). Papers and reports documenting the accuracy of the FSSP include Refs. 1 and 23.

The KLD hot wire DC-2A is based on the heat transfer from a heated wire to a drop striking the wire (24-25). Some discussion of accuracy may be found in Ref. 25.

The Bete Droplet Analyzer is a video imaging system using strobe illumination and digital image analysis (26).

In addition to the limitations of the instrumentation listed in some of the references above, the capabilities of the instrument operators may have had an effect on the results.

Table 4 includes an indication of how each type of instrument acquires a sample. Each instrument includes a designation as to whether it is a point or line-of-sight integral sample, and a designation as spatial or temporal (see Table 5 and below). An instrument is considered as sampling at a point, for the purpose of this report, if its sample volume is small relative to the diameter of the spray cone at the measurement location. All instruments in Table 4 except the Malvern laser-diffraction units are considered as measuring at a point, while the Malvern integrates all along the path formed by the intersection of the laser beam with the spray. Figure 1 illustrates a cross section of a typical spray from a pressure swirl atomizer such as the ones used for these tests. Also shown in the figure is the sampling path of the laser beam of a Malvern through various chords of the spray. It is clear from Figure 1 that the line-of-sight integral values are not directly comparable with results from point measuring instruments except at the edge of the spray. Therefore, some comparisons presented in the results are restricted to measurements near the edge of the spray.

In order to extend the comparisons between the Malvern line-of-sight measurements and the point measurements of other instruments to the interior of the spray, a deconvolution procedure developed by Hammond (27) was used to convert line-of-sight data from one typical calibrated Malvern into equivalent point data. It must be noted that this is not common practice, but it offers a unique opportunity for comparison of results from Malvern instruments with other types of instruments. It is also possible to convert point measurements into line-of-sight equivalent values (6), although that approach was not used here.

The other distinction between the sampling processes of the different instruments has to do with the effect of drop velocity on the measurement. The terminology which has developed classifies the sampling processes as spatial or temporal. Table 5 illustrates the difference between the two types of sample weighting. Instruments such as the two PMS models, the KLD hot wire and the Aerometrics measure the number of drops per unit time which pass through the sample volume, and the signal is proportional to this temporal frequency; therefore the sampling process is called temporal. The Malvern laser-diffraction and Bete video imaging instruments, on the other hand, respond in proportion to the number of drops within the sample volume, which is proportional to the spatial frequency of the drops (e.g., drops/cm in one dimension as shown in Table 5). This is referred to as a spatial sample. If the velocities of all drops are the same, or if the velocities vary but are not correlated with size, then the temporal and spatial values are identical. However, in many spray systems the velocities are corrrelated with size due to variations in drag with size, and the temporal and spatial averages are different, as for the Downstream Condition in Table 5. Because the Aerometrics instrument correlates velocity and size, it can compute a spatial average as well as the temporal average which it measures directly. The conversion process used in the Aerometrics instrument has some shortcomings (6), but it does provide some quantitative basis for comparison. Based on Aerometrics data, differences between spray measurements due to temporal/spatial sampling differences were less than 25 percent in value of SMD for these sprays and measurement locations. Further details on these differences are given in the Results section.

For the Aerometrics instruments, the results are based on the temporal sampling process except where stated otherwise. Caution must be exercised in comparing results for the Aerometrics instruments from different figures because the spatial and temporal values used in various figures are slightly different.

RESULTS

The results of the round robin spray tests are presented in Figures 2-27, and in Table 6. A complete set of tabulated results is also given in Appendix A. Results are expressed as Sauter mean diameter (SMD), also called D_{32}, and relative span, defined as (28),

$$\text{Span} = (D_{v0.9} - D_{v0.1})/D_{v0.5}$$

where $D_{v0.9}$ is the diameter at which 90 percent of the spray volume is contained in drops of smaller sizes, and similarly for $D_{v0.1}$ and $D_{v0.5}$. Results for the Parker-Hannifin (P/H) atomizer are presented first for the low- and high-pressure differentials, and then for the Delavan (DLN) atomizer at low- and high-pressure differentials.

Statistical analyses of the measurements at the centerline and the edge of the spray are presented in Table 6. A mean SMD is provided for each set of comparable data, as well as the total spread or range of SMDs in the reported results, and the range expressed as a fraction of the mean. In cases where at least three values were available, the standard deviation of the SMDs and the coefficient of variation were reported. One column of Table 6 indicates the corresponding figure which provides a visual presentation of the same results.

Results for Parker-Hannifin Atomizer at 345 kPa

Figure 2 offers a comparison of SMD's measured by 9 instruments for the P/H atomizer at a differential pressure of 345 kPa (50 psid). These results are not directly comparable because of the sampling effects previously discussed. However, the point measurements and line-of-sight integral measurements should be comparable near the edge of the spray (see Figure 1), except for the relatively minor (less than 10 percent for this condition) differences due to temporal/spatial sampling effects. Thus, the large differences in results shown in Figure 2 near the edge of the spray cannot be attributed solely to sampling effects, and they reflect actual instrument differences.

In order to arrive at comparable results, all the Malvern data are shown in Figure 3, which results in a coefficient of variation, CV, (defined as standard deviation/mean) at the centerline of .062. Omitting laboratory P and uncalibrated Malverns, the 4 remaining instruments (B, D, E, and J) had a CV on the centerline of .060 and at the edge of .031. Tests at laboratory P involved sprays into stagnant air, which may have affected the spray characteristics at the edge due to recirculation of the smaller drops. At the control laboratory, the P/H atomizers at 345 kPa had a CV on the centerline of .03. These results have the very important implication that a

reproducible spray test was defined and conducted at various laboratories for the P/H atomizer, and this conclusion was also confirmed for the 689 kPa case for this atomizer based on similar results.

Results for the temporally sampling instruments are shown in Figure 4 and Table 6. These results indicate significant variations, even between the two Aerometrics instruments (N and Q).

From Figure 3 it may be seen that the Malvern instrument at laboratory B was typical of the calibrated Malverns. In order to compare the Malvern line-of-sight intergal data with the point measurements of other instruments, Malvern data were obtained at laboratory B in small radial steps and then Hammond's (27) deconvolution procedure was used to convert the line-of-sight data to point data. In Figure 5 the deconvoluted (point) Malvern data are compared with the Aerometrics data from laboratory Q which are expressed as spatial measurements in this figure. Aerometrics data converted to the spatially sampled format were not available from laboratory N, but comparison of Figures 4 and 5 shows that the deconvoluted Malvern data would lie in between the two sets of Aerometrics data. (As shown in Figure 6, the conversion from temporal to spatial reduces the SMD's only slightly, a maximum of 9.1 percent.) Thus, the deconvoluted Malvern data (B) is similar to the two sets of Aerometrics data (N and Q) but agrees poorly with the PMS data (C).

The relative spans shown in Figure 7 show a narrower distribution towards the edge of the spray. In this case, both line-of-sight and point data are shown in the same figure.

Results for Parker-Hannifin Atomizer at 689 kPa

Figure 8 shows the SMD's measured by 11 instruments for the P/H atomizer at 689 kPa. Figure 9 is the same data for only the Malvern instruments. Excluding the uncalibrated older instrument at laboratory I (model ST1800) and the static air results from laboratory P, the agreement for the remaining four instruments (B, D, E, and J) is excellent, with a CV on the centerline of 0.088 and at the edge of 0.024. As mentioned previously, this indicates a repeatable spray test was defined and produced at different laboratories.

Figure 10 shows a comparsion of the temporally sampling instruments, including two Aerometrics instruments and one KLD hot wire and the combined PMS data FSSP/OAP. Excluding the PMS instruments, the CV on the centerline is 0.194 and at the edge is 0.115, indicating reasonable agreement (excluding the considerably larger PMS results).

By deconvoluting the Malvern data from laboratory B to get point measurements and comparing with the Aerometrics spatial data as shown in Figure 11, it may be seen that the results from the two instruments agree closely at these conditions. From Figure 12, it may be noted that the maximum difference between spatial and temporal measurements is only 5.6 percent, so that Malvern data in Figure 11 may be approximately compared with the temporal data in Figure 10. The Malvern data (B) follow closely the Aerometrics data (N and Q), are generally somewhat larger than the KLD hot wire (F), and are much smaller than the PMS FSSP/OAP (C).

The span data in Figure 13 are a combination of all instruments and sampling types.

Results for Delavan Atomizer at 276 kPA

A comparison of the SMD data obtained by 10 instruments for the Delavan atomizer at a differential pressure of 276 kPa (40 psid) is given in Figure 14. The data for Malvern instruments is shown in Figure 15. Excluding the uncalibrated model ST1800 used by laboratory H, the measurements on the centerline agree very well with a CV of 0.046. Again laboratory P, with a spray into stagnant air, shows lower values near the edge, but the agreement is still fair for the calibrated Malverns with a CV of 0.157.

Data for the temporally sampling instruments are shown in Figure 16. Again the PMS instruments (C and L) tend to exhibit values on the high side while the Aerometrics instruments (K and O) tend to be lower. However, in contrast with the results for the P/H atomizers, the KLD hot wire (F) tends to agree more closely with the PMS results than the Aerometrics results. The overall scatter between results is significant with a CV on the centerline of 0.244, and on the edge of 0.150. These

differences appear to be systematic and depend on instrument design and are not explainable by differences in the atomizers.

Figure 17 represents a comparison of 3 different types of instruments which all produce a spatial measurement. These include a Malvern after deconvolution (B), two Aerometrics (K and O), and a Bete video imaging instrument (M). The Bete agrees closely with the Aerometrics instruments, and the Malvern is similar except near the centerline where it is lower. The CV on the centerline is 0.149 and at the edge (51 mm) is 0.104. Excluding the Malvern data, the CV on the centerline is 0.051 and on the edge (51 mm) is 0.078. These latter two values are probably within the reproducibility of the spray.

At the edge of the spray, the Malvern data are essentially point data (see Figure 1) and can be compared directly (without deconvolution) with the other spatial point data as shown in Figure 18. This figure includes data from four Malverns (B, G, H, and P), two Aerometrics (K and O) and the Bete instrument (M). The CV at the edge (51 mm) is 0.176. Excluding the static air tests at laboratory P, the CV is 0.139.

The difference between spatial and temporal measurements is somewhat larger for the Delavan atomizer than for the P/H atomizer with the temporal values as much as 24.8 percent larger than the spatial values as shown in Figure 19. Comparing Figures 16-18 and accounting for the differences between spatial and temporal sampling from Figure 19, it may be seen that the Malvern, Bete, and Aerometrics data form a lower band while the PMS and KLD data are somewhat larger.

The relative span data for the Delavan atomizer are shown in Figure 20.

Results for Delavan Atomizer at 689 kPa

Results for SMD measurements for 10 instruments for the Delavan atomizer at at differential pressure of 689 kPa (100 psid) are shown in Figure 21. Comparison with Figure 14 shows that most of the differences between instruments shown in Figure 21 are systematic and depend on instrument design. The Malverns (B, G, H, and P) tend to form a band of agreement with the uncalibrated older ST1800 of laboratory H slightly larger near the centerline and laboratory P falling low near the edge. The

Aerometrics (K and O) and Bete (M) results are grouped with the Malvern data. The PMS data (C and L) are significantly higher and the KLD data (F) agree with the lower group near the centerline and then increase rapidly to agree with the PMS data near the edge.

Figure 22 is the same results limited to Malvern instruments. The agreement at centerline excluding the uncalibrated older ST1800 of laboratory H is excellent, with a CV of 0.007. These results again support the reproducibility of the spray test at different laboratories. From Figure 22 it may be seen that the agreement through the spray is excellent, with laboratory P dropping lower again near the edge.

The results for the temporal sampling instruments exhibit a large amount of scatter as shown in Figure 23. The CV on the centerline is 0.731 and on the edge is 0.272. The Aerometrics data (K and O) agree well between instruments but are much lower than the PMS data (C and L). The KLD data (F) agree with the Aerometrics data close to the centerline and the PMS data at the edge.

The spatial point measurements agree fairly well as shown in Figure 24 with the deconvoluted Malvern data slightly lower than the others near the centerline. Instruments include two Aerometrics (K and O), a Bete (M), and a Malvern (B). The CV on the centerline is 0.355 and on the edge is 0.129. Excluding the Malvern, the CV is 0.214 on the centerline and 0.123 at the edge.

Examining all the spatial data of the edge of the spray, including the Malvern line-of-sight data, good agreement is obtained as shown in Figure 25. The CV at 63 mm from the centerline is 0.095, probably within the reproducibility of the test.

The differences between spatial and temporal sampling are smaller than for the 276 kPa case, as shown in Figure 26, with a maximum difference of 20.5 percent.

The SMD data at 689 kPa are similar in terms of instrument trends to those at 276 kPa. The Malvern, Aerometrics, and Bete data follow similar trends, with the deconvoluted Malvern data somewhat lower near the centerline. The PMS data are systematically larger than the others, and the KLD data follow a different trend.

The relative span data for all instruments are shown in Figure 27.

SUMMARY

1. A spray test was defined which allowed for reproducible sprays. This was verified by laboratories using calibrated Malverns. The coefficient of variation (CV), which is defined as the standard deviation/mean, indicated good agreement on the spray centerline for both the Parker-Hannifin and Delavan atomizers at the low and high pressures with CV values for calibrated Malverns of 0.069, 0.081, 0.046, and 0.007, respectively. Thus, the spray characteristics were reproducible to within about 10 or 15 percent. Some problems of spray reproducibility were encountered. Laboratory P used static air, instead of flowing air, and that may have affected spray characteristics near the spray edge. Laboratory L measured a low flow number for a Delavan atomizer.

2. Variations in SMD's measured by different instruments were beyond what would logically be attributed to spray reproducibility or theoretical differences in sampling effects (i.e., line-of-sight versus point, and spatial versus temporal). These data strongly suggest systematic trends for instrument responses based on instrument designs. The "correct" drop sizes for these tests are not known, of course. The results for the Malvern, Aerometrics, and Bete instruments roughly grouped together (with scatter as shown). The deconvoluted Malvern SMD's were sometimes the lowest of this group, particularly near the centerline. The SMD's from the PMS instrument were systematically larger than the first group (Malvern, Aerometrics, and Bete). The KLD results were generally in the lower grouping (Malvern, Aerometrics, and Bete) for the spray using calibration fluid, but they spanned a path between that lower group and the PMS data for the water spray.

3. The agreement among the Malvern instruments with custom detector response factors appeared to be superior to the Malvern instruments without custom factors for measurements through the spray centerline. Measurements through the spray edge appeared to be more dependent on the experimental conditions. The agreement among these "calibrated" Malverns was superior to the agreement between Aerometrics instruments. There were insufficient numbers of other instruments of one design for this type of comparison. The good agreement between Malverns might be related to the line-of-sight integration through actual spatial variations in the sprays, which would affect point measuring instruments more strongly.

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TABLE 1. SPRAY DROP-SIZE CHARACTERISTICS OF DELAVAN TEST ATOMIZERS, AS MEASURED AT CONTROL LABORATORY USING MALVERN LASER-DIFFRACTION INSTRUMENT

Atomizer Number	SMD at 2 Differential Pres. (μm)	
	276 kPa	689 kPa
1	99.7	56.8
2	102.6	57.6
3	99.6	56.7
4	96.4	55.3
5	94.9	55.6
6	95.9	53.7
7	95.2	54.9
8	103.5	56.4
9	98.9	56.8
10	101.9	55.0
11	98.9	54.5
Mean (μm)	98.9	55.8
Standard Deviation (μm)	2.86	1.17
Coeff. of Variation (%)	2.9	2.1

TABLE 2. SPRAY DROP-SIZE CHARACTERISTICS OF PARKER-HANNIFIN TEST ATOMIZERS, AS MEASURED AT CONTROL LABORATORY USING MALVERN LASER-DIFFRACTION INSTRUMENT

Atomizer Number	SMD at Differential Pres. (μm)	
	345 kPa	689 kPa
1	35.8	28.3
3	33.7	26.1
4	34.1	28.6
5	34.5	27.0
6	32.2	24.9
7	32.8	25.0
8	34.1	26.8
9	35.5	26.3
10	34.5	26.5
11	33.9	28.4
Mean (μm)	34.11	26.79
Standard Deviation (μm)	1.03	1.26
Coeff. of Variation (%)	3.0	4.7

TABLE 3. RECOMMENDED AND ACTUAL SPRAY CONDITIONS

Laboratory Test Condition	Recommended Range	A	B	B	C	C	D	E	F	F	G	H
Atomizer Type	P/H or DLN	P/H 4	P/H 6	DLN 4	P/H 8	DLN 10	P/H 6	P/H 3	P/H 5	DLN 11	DLN 4	DLN 1
Test Fluid	Distilled Water or Cal. Fluid	Cal.	Cal.	Water	Cal.	Water	Cal.	Cal.	Cal.	Water	Water	Water (Not dist.)
Flow Rate @ 689 kPa (g/s)	P/H = 1.86 DLN = 20.5	1.76	1.93	20.21	1.90	19.82	1.94	1.94	-	-	18.23	18.6
Fluid Temp. (°C)	26.7 ± 2.8	30 ± .5	25	26.7	27.2	27.8	26.7 ± 1.1	23.9	18.3	23.9	23	21.1
Air Temp. (°C)	21 - 28*	30.5	23.9	23.9	-	28.3	22.2	26.7	18.3	23.9	23	23.9
Air Vel. (m/s)	0.6 - 3.0*	0.3	1.98	1.98	-	-	0.06	-	-	-	1	-
Air Pres. (kPa)	(Report)	97.08	98.6	98.6	-	99.2	98.1	98.6	-	-	100.95	-
Rel. Humidity (%)	(Report)	-	-	74	-	58	-	-	-	85 ± 2	53.5	-
Atomizer Orientation	Vertical or Horizontal	V	H	H	H	H	V	V	V	V	V	H
Atomizer Pressure Differential (kPa)	DLN: 276 ± 6 689 ± 14 P/H: 345 ± 7 689 ± 14	(Not Reported)										

* Within this range if possible

TABLE 3. RECOMMENDED AND ACTUAL SPRAY CONDITIONS (Cont.)

Laboratory Test Condition	Recommended Range	I	J	K	L	M	N	O	P	P	Q
Atomizer Type	P/H or DLN	P/H 7	P/H 1	DLN 10	DLN 3	DLN 5	P/H 3	DLN 6	P/H 9	DLN 2	DLN 4
Test Fluid	Distilled Water or Cal. Fluid	Cal.	Cal.	Water	Water	Water	Cal.	Water	Cal.	Water	Water
Flow Rate @ 689 kPa (g/s)	P/H = 1.86 DLN = 20.5	1.95	-	19.20	16.53	18.48	1.94	18.76	1.88	21.31	20.21
Fluid Temp. (°C)	26.7 ± 2.8	23.9	26.7	22.2	21.1	26.7	23.9	18.9	21.1	21.1	26.7
Air Temp. (°C)	21 - 28*	21.1	23.9	22.2	21.1	22.2	26.7	20.6	21.1	21.1	23.9
Air Vel. (m/s)	0.6 - 3.0*	4.6	-	1.2	-	-	-	2.48	-	0	1.98
Air Pres. (kPa)	(Report)	101.3	100.0	101.3	-	101.3	98.6	100.00	101.3	101.1	98.6
Rel. Humidity (%)	(Report)	-	-	70	51 - 59	64	-	58	-	-	74
Atomizer Orientation	Vertical or Horizontal	H	V	V	V	V	V	V	V	V	H
Atomizer Pressure Differential (kPa)	DLN: 276 ± 6 689 ± 14 P/H: 345 ± 7 689 ± 14	(Not Reported)									

*Within this range if possible

TABLE 4. INSTRUMENTATION USED AT VARIOUS LABORATORIES PARTICIPATING IN SPRAY TESTS

Laboratory	Inst. Type	Inst. Size Range (μm)	Sampling Type*	Custom Detector Responsivities (Malvern only)	Atomizers Tested
A	Malvern, Model 2200	5.8 - 564	Spatial, L.O.S.	N	P/H
B	Malvern, Model 2200	5.8 - 564	Spatial, L.O.S.**	Y	DLN, P/H
C	PMS, Models FSSP-100 and OAP-260X	5 - 1875	Temporal, Point	—	DLN, P/H
D	Malvern, Model 2600	5.8 - 564	Spatial, L.O.S.	Y	P/H
E	Malvern, Model 2200	5.8 - 564	Spatial, L.O.S.	Y	P/H
F	KLD Hot Wire, DC - 2A	1 - 450	Temporal, Point	—	DLN, P/H
G	Malvern, Model 2200	5.8 - 564	Spatial, L.O.S.	Y	DLN
H	Malvern, Model 1800	5.8 - 564	Spatial, L.O.S.	N	DLN
I	Malvern Model 1800	5.8 - 564	Spatial, L.O.S.	N	P/H
J	Malvern, Model 2600	5.8 - 564	Spatial, L.O.S.	Y	P/H
K	Aerometrics, P/DPA	—	Temporal, Point***	—	DLN
L	PMS, Model OAP-2D-GA1	28 - 2062	Temporal, Point	—	DLN
M	Bete Droplet Analyzer	6.3 - 1260	Spatial, Point	—	DLN
N	Aerometrics, P/DPA	—	Temporal, Point	—	P/H
O	Aerometrics, P/DPA	—	Temporal, Point***	—	DLN
P	Malvern, Model 2600	5.8 - 564	Spatial, L.O.S.	Y	DLN, P/H
Q	Aerometrics, P/DPA	—	Temporal, Point***	—	P/H

* L.O.S. = Line-of-Sight Average
Point = Measurement in a volume whose dimensions are small relative to the width of the spray at the measurement location.
** Data also converted to spatial point equivalent using deconvolution procedure
*** Data taken as temporal measurement, but converted also to spatial equivalent data.

TABLE 5. COMPARISON OF TEMPORAL AND SPATIAL SAMPLING

Temporal Sampling Instruments, Such As Single Particle Counters, Register Signals Proportional to Temporal Frequency, i.e., counts/sec

Spatial Sampling Instruments, Such as Photographic or Laser Diffraction, Register Signals Proportional (in 1 Dimension) to Spatial Frequency, i.e. counts/meter

	Initial Condition	Downstream Condition
Atomizer	O O O O O	O O O O O O O
	o o o o o o o o o o	oooooooooooooooooooooooooo

Initial Condition:

Size	Temporal Freq.	Velocity	Spatial Freq.
200 μm	10/sec	2 m/sec	5/m
100 μm	20/sec	2 m/sec	10/m

Temporal Sample

$$D_{10} = \frac{10 \times 200 + 20 \times 100}{30} = 133\ \mu m$$

Spatial Sample

$$D_{10} = \frac{5 \times 200 + 10 \times 100}{15} = 133\ \mu m$$

Downstream Condition:

Size	Temporal Freq.	Velocity	Spatial Freq.
200 μm	10/sec	2 m/sec	5/m
100 μm	20/sec	1 m/sec	20/m

Temporal Sample

$$D_{10} = \frac{10 \times 200 + 20 \times 100}{30} = 133\ \mu m$$

Spatial Sample

$$D_{10} = \frac{5 \times 200 + 20 \times 100}{25} = 120\ \mu m$$

TABLE 6. STATISTICS REGARDING MEASUREMENTS OF SAUTER MEAN DIAMETER

Inst. Labs Type	Figure Ref	Meas. Location (mm)	Number of Meas.	Mean SMD (μm)	Std. Dev. SMD (μm)	Coeff. of Variation	Range (μm)	Range / Mean
A. PARKER HANNIFIN ATOMIZER, 345 kPa								
Malvern all, A,B,D,E,J,P	3	0	6	36.4	2.25	.062	6.5	.178
Malvern all, A,B,D,E,J,P	3	44	6	75.4	9.56	.145	26.5	.351
Malvern calib., B,D,E,J,P	3	0	5	36.3	2.51	.069	6.5	.179
Malvern calib., B,D,E,J,P	3	44	5	76.0	10.57	.139	26.5	.349
Malvern calib., B,D,E,J (omit P)	3	0	4	37.1	2.24	.060	5.3	.143
Malvern calib., B,D,E,J (omit P)	3	44	4	80.6	2.50	.031	5.5	.068
Temporal point, C,N,Q	4	0	3	27.8	15.32	.551	30.0	1.079
Temporal point, C,N,Q	4	44	3	116.3	45.27	.389	87.6	.753
Spatial point, B*,Q	5	0	2	20.0	-	-	8.9	.445
Spatial point, B*,Q	5	44	2	93.3	-	-	10.1	.108
B. PARKER HANNIFIN ATOMIZER, 689 kPa								
Malvern all, A,B,D,E,I,J,P	9	0	7	31.1	9.11	.293	26.0	.835
Malvern all, A,B,D,E,I,J,P	9	44	7	70.8	15.21	.215	43.0	.608
Malvern calib., B,D,E,J,P	9	0	5	27.6	2.24	.081	5.7	.204
Malvern calib., B,D,E,J,P	9	44	5	68.7	17.91	.261	41.4	.602
Malvern calib., B,D,E,J (omit P)	9	0	4	27.9	2.46	.088	5.7	.202
Malvern calib., B,D,E,J (omit P)	9	44	4	76.7	1.85	.024	4.2	.055
Temporal point, C,F,N,Q	10	0	4	20.6	20.28	.985	42.8	2.076
Temporal point, C,F,N,Q	10	44	4	103.7	55.63	.537	120.0	1.158
Temporal, F,N,Q (omit C)	10	0	3	10.5	2.04	.194	3.8	.358
Temporal, F,N,Q (omit C)	10	44	3	76.1	8.74	.115	17.0	.223
Spatial point, B*, Q	11	0	2	11.7	-	-	0.8	.068
Spatial point, B*, Q	11	44	2	76.8	-	-	8.1	.105

TABLE 6. STATISTICS REGARDING MEASUREMENTS OF SAUTER MEAN DIAMETER (Cont.)

Inst. Labs Type	Figure Ref	Meas. Location (mm)	Number of Meas.	Mean SMD (μm)	Std. Dev. SMD (μm)	Coeff. of Variation	Range (μm)	Range / Mean
C. DELAVAN ATOMIZER, 276 kPa								
Malvern all, B,G,H,P	15	0	4	108.7	11.50	.106	27.0	.248
Malvern all, B,G,H,P	15	64	4	132.5	41.25	.311	50.8	.383
Malvern calib., B,G,P	15	0	3	103.3	4.71	.046	9.0	.087
Malvern calib., B,G,P	15	64	3	106.0	16.65	.157	31.8	.300
Temporal point, C,F,K,L,O	16	0	5	131.5	32.14	.244	81.4	.619
Temporal point, C,F,K,L,O	16	64	5	187.9	28.13	.150	69.2	.368
Spatial point, B*,K,M,O	17	0	4	83.8	12.5	.149	27.1	.324
Spatial point, B*,K,M,O	17	51	4	151.1	15.6	.104	34.6	.229
Spatial point, K,M,O (omit B)	17	0	3	89.7	4.6	.051	8.5	.095
Spatial point, K,M,O (omit B)	17	51	3	148.4	11.7	.079	21.0	.142
Spatial edge, B,G,H,K,M,O,P	18	51	7	129.2	22.76	.176	63.8	.494
Spatial edge, B,G,H,K,M,O (omit P)	18	51	6	134.9	18.73	.139	48.9	.362
D. DELAVAN ATOMIZER, 689 kPa								
Malvern all, B,G,H,P	22	0	4	63.0	15.33	.243	31.0	.492
Malvern all, B,G,H,P	22	64	4	103.5	8.85	.086	18.7	.181
Malvern calib., B,G,P	22	0	3	55.4	0.41	.007	0.8	.014
Malvern calib., B,G,P	22	64	3	102.4	10.47	.102	18.7	.183
Temporal point, C,F,K,O	23	0	4	59.9	43.75	.731	94.9	1.586
Temporal point, C,F,K,L,O	23	64	5	170.3	46.30	.272	116.6	.685
Spatial point, B*,K,M,O	24	0	4	30.6	10.9	.355	25.9	.848
Spatial point, B*,K,M,O	24	64	4	111.1	14.3	.129	31.4	.283
Spatial point, K,M,O (omit B)	24	0	3	35.0	7.51	.214	14.9	.426
Spatial point, K,M,O (omit B)	24	64	3	106.4	13.09	.123	26.1	.245
Spatial edge, B,G,H,K,M,O,P	25	64	7	104.7	9.93	.095	29.7	.284

* Deconvoluted values

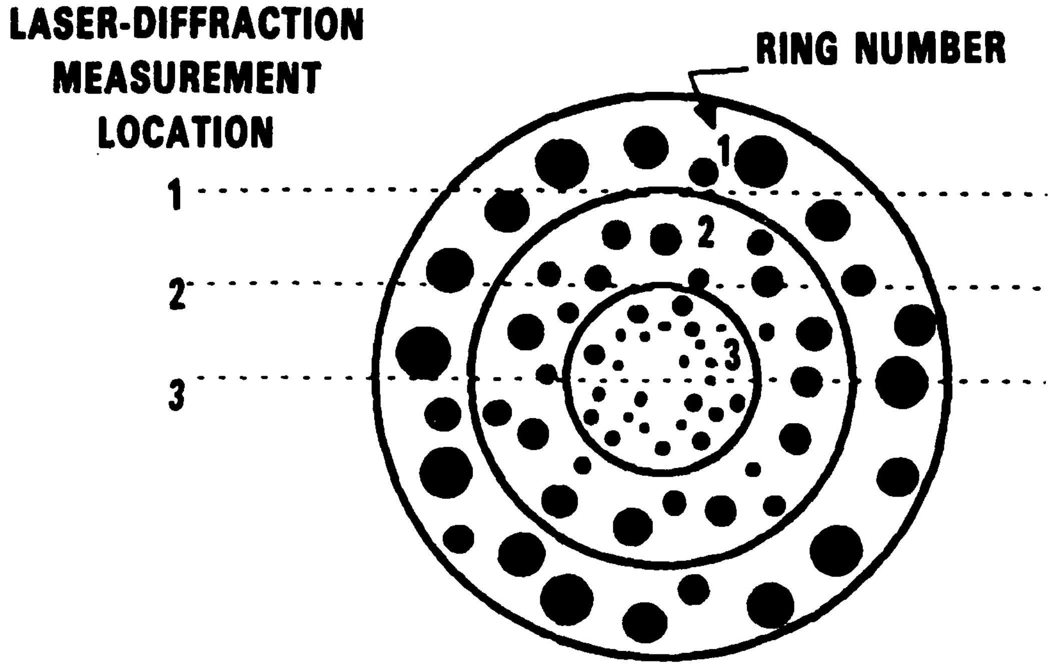

FIGURE 1. SPRAY STRUCTURE FOR SIMPLEX ATOMIZER, AND MALVERN SAMPLING LOCATIONS

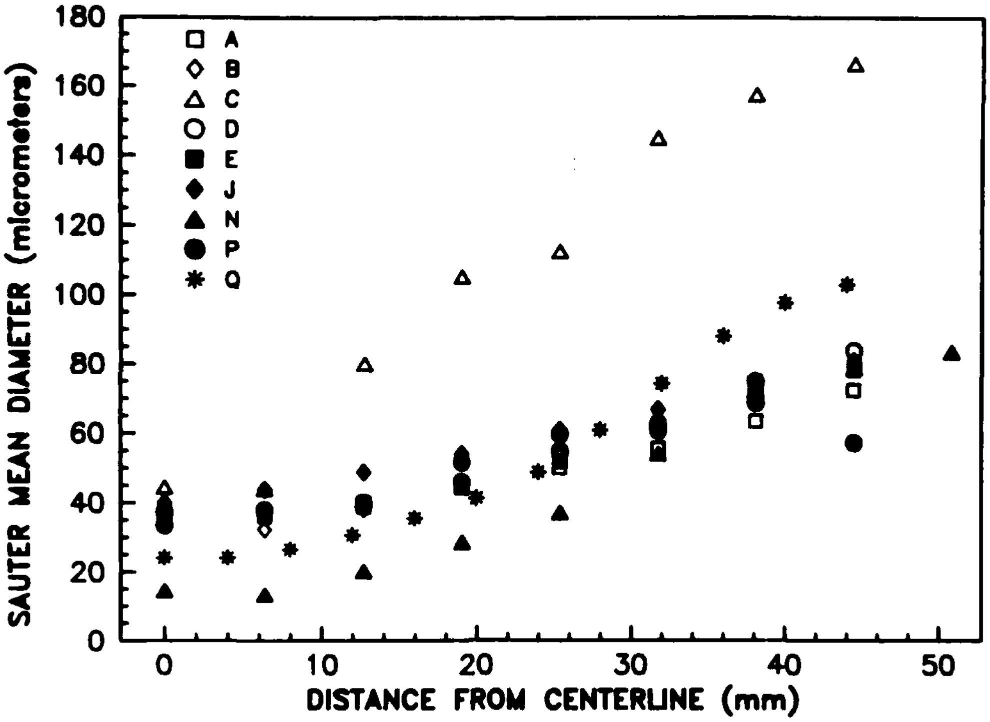

FIGURE 2. SMD DATA FOR ALL INSTRUMENTS, P/H AT 345 kPa

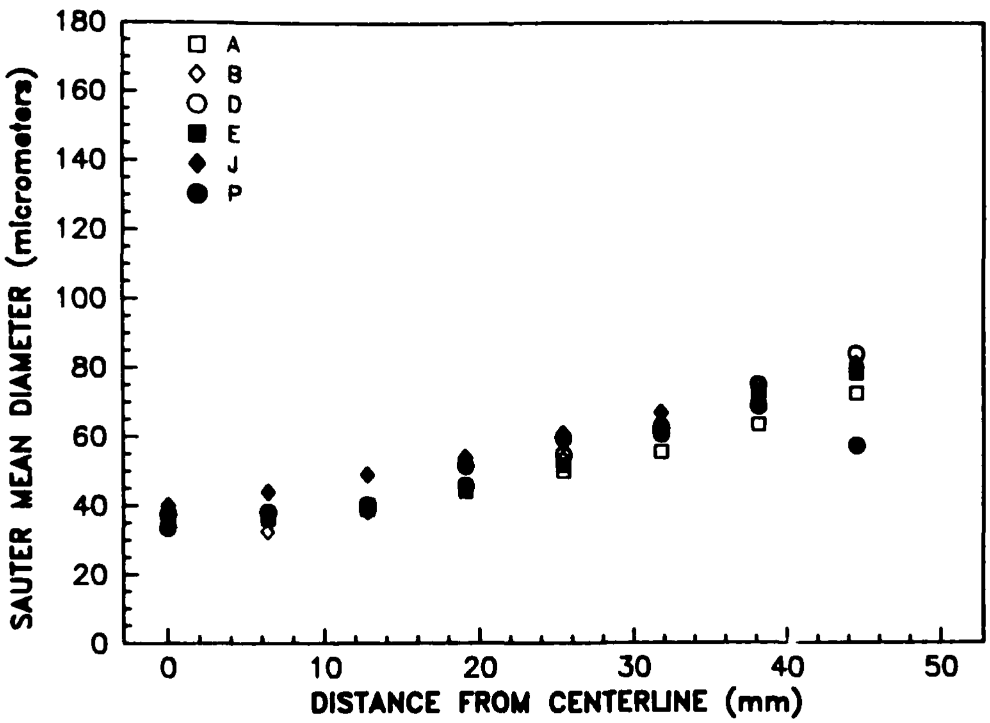

FIGURE 3. MALVERN LINE-OF-SIGHT SMD DATA, P/H AT 345 kPa

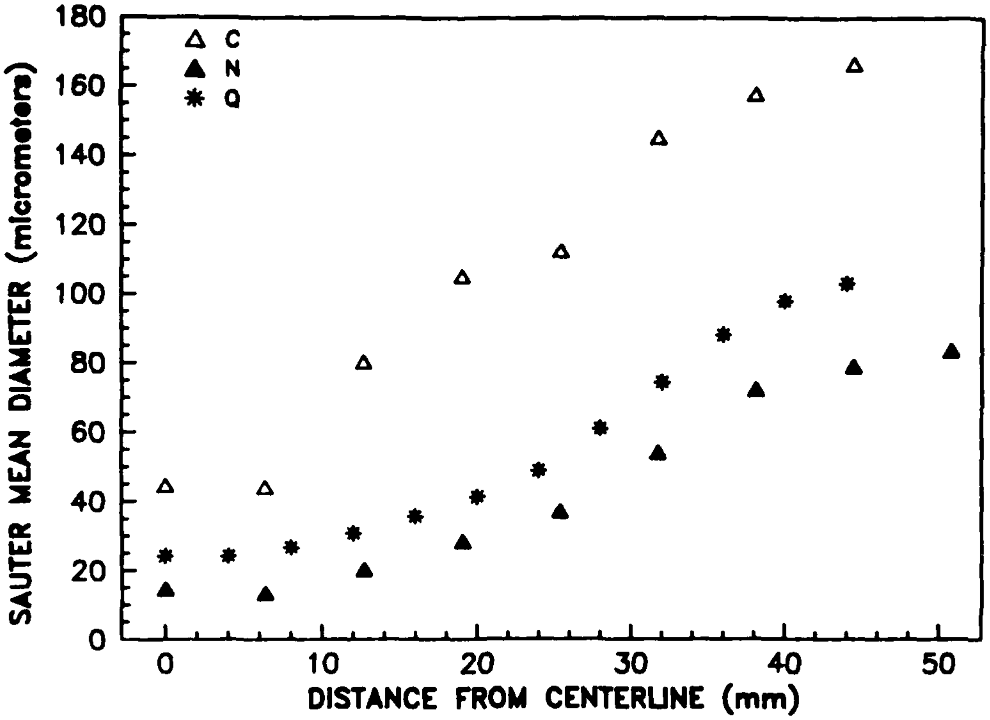

FIGURE 4. TEMPORAL (OR FLUX-SENSITIVE) SMD DATA, P/H AT 345 kPa

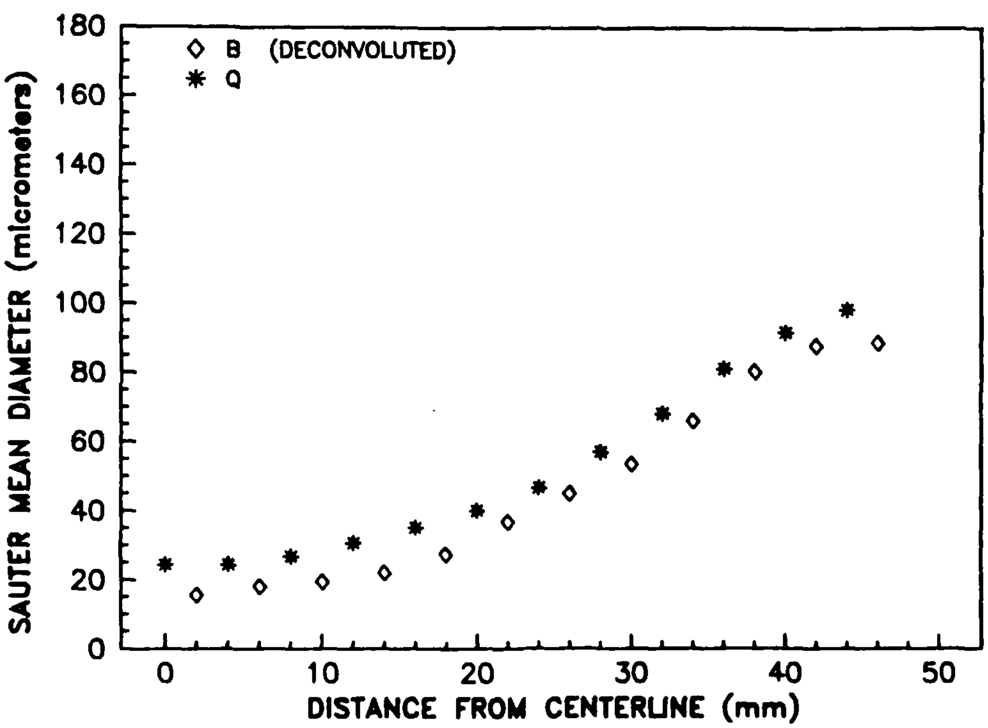

FIGURE 5. SPATIAL (OR CONCENTRATION-SENSITIVE) POINT SMD DATA, P/H AT 345 kPa

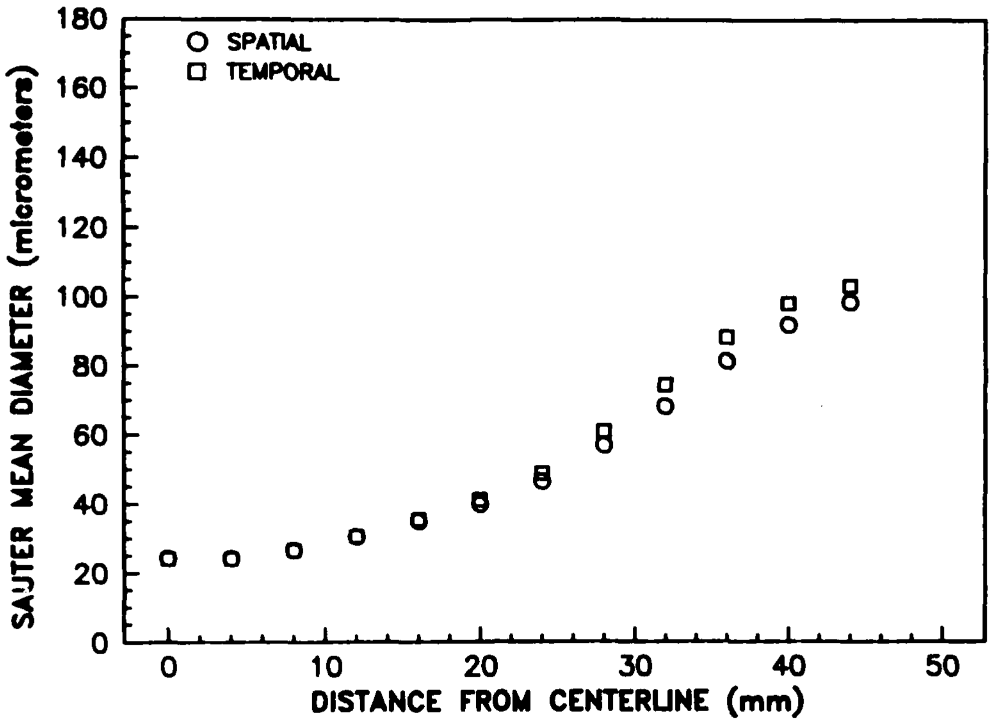

FIGURE 6. TEMPORAL VERSUS SPATIAL SMD DATA (AEROMETRICS), P/H AT 345 kPa

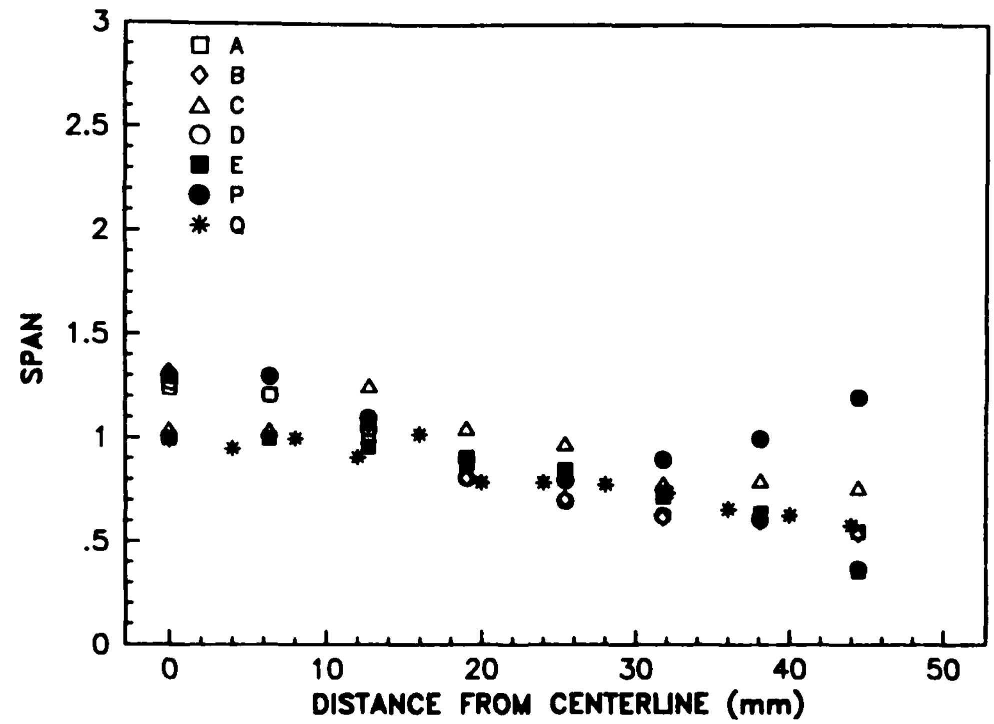

FIGURE 7. SPAN DATA FOR ALL INSTRUMENTS, P/H AT 345 kPa

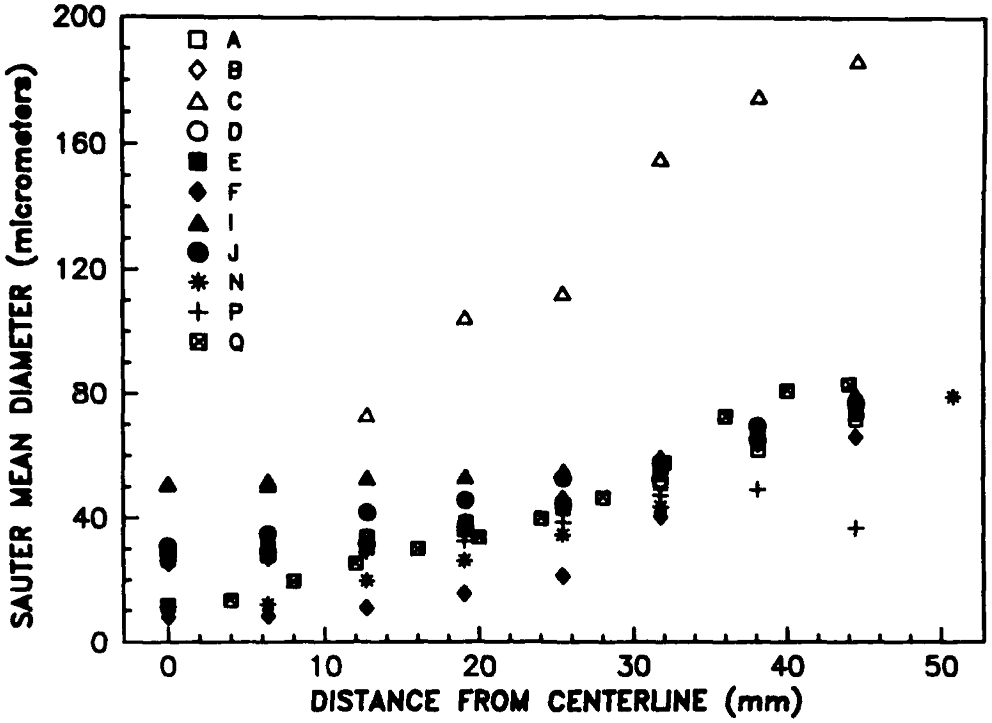

FIGURE 8. SMD DATA FOR ALL INSTRUMENTS, P/H AT 689 kPa

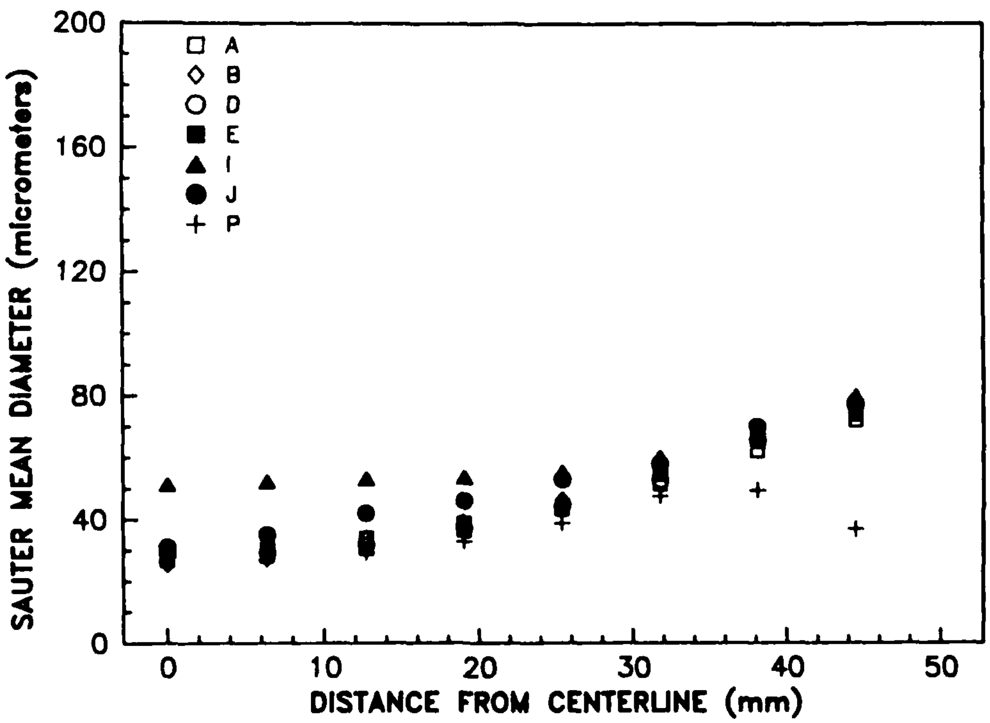

FIGURE 9. MALVERN LINE-OF-SIGHT SMD DATA, P/H AT 689 kPa

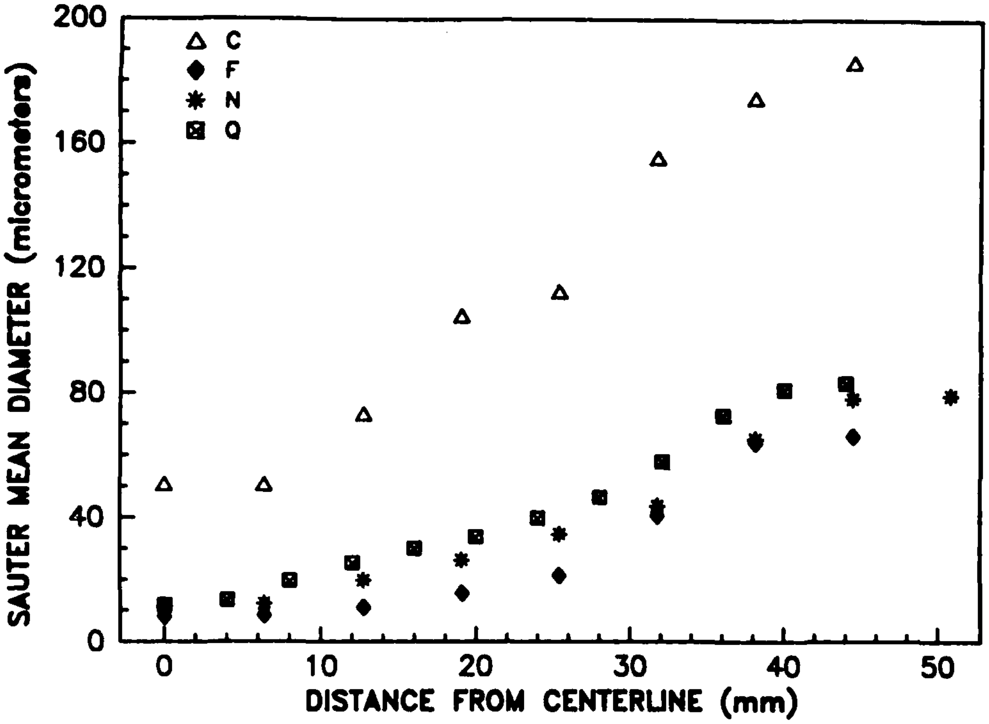

FIGURE 10. TEMPORAL (OR FLUX-SENSITIVE) SMD DATA, P/H AT 689 kPa

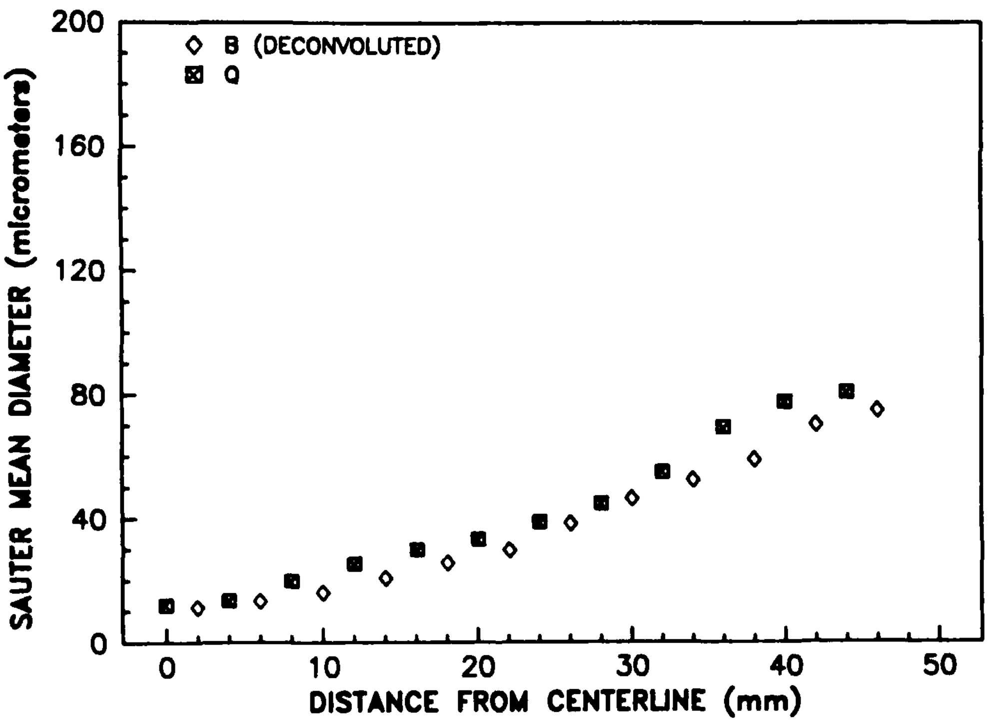

FIGURE 11 . SPATIAL (OR CONCENTRATION-SENSITIVE) POINT SMD DATA, P/H AT 689 kPa

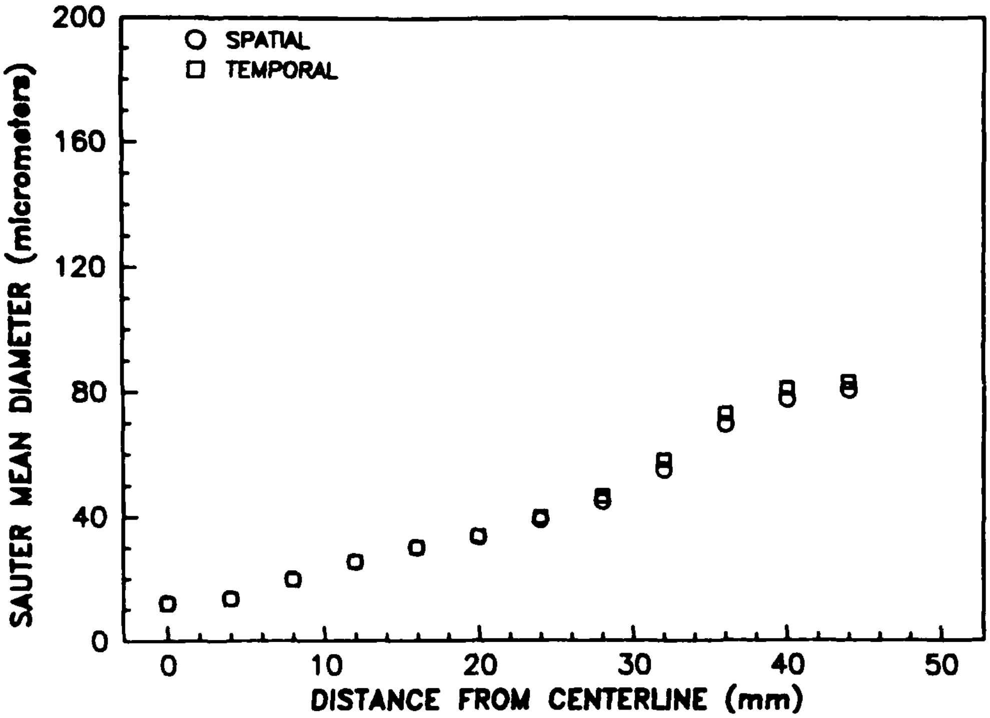

FIGURE 12. TEMPORAL VERSUS SPATIAL SMD DATA (AEROMETRICS), P/H AT 689 kPa

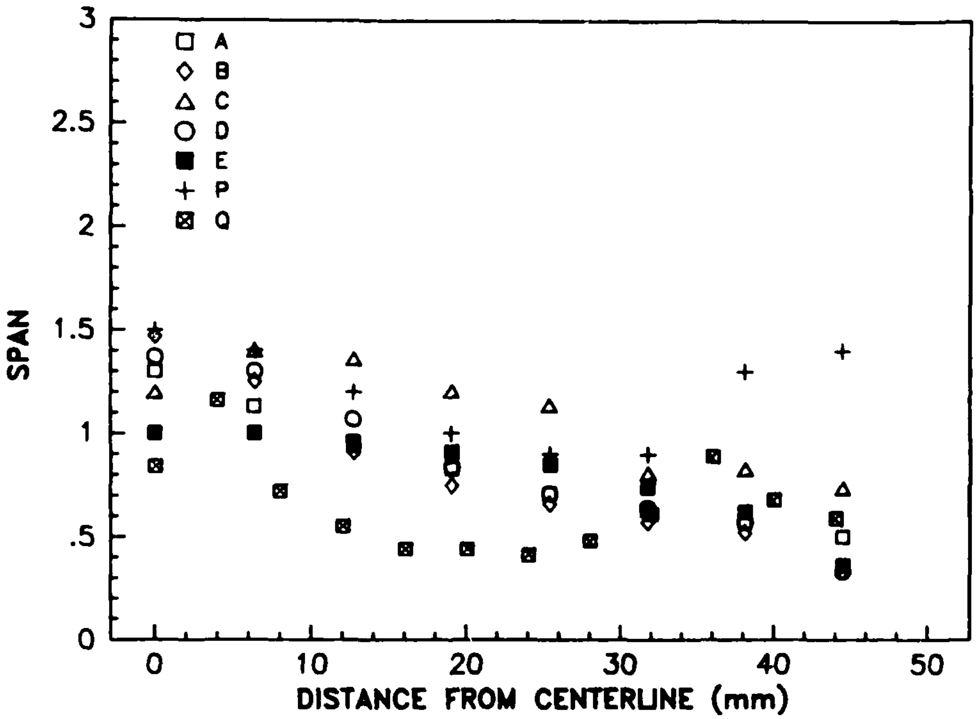

FIGURE 13. SPAN DATA FOR ALL INSTRUMENTS, P/H AT 689 kPa

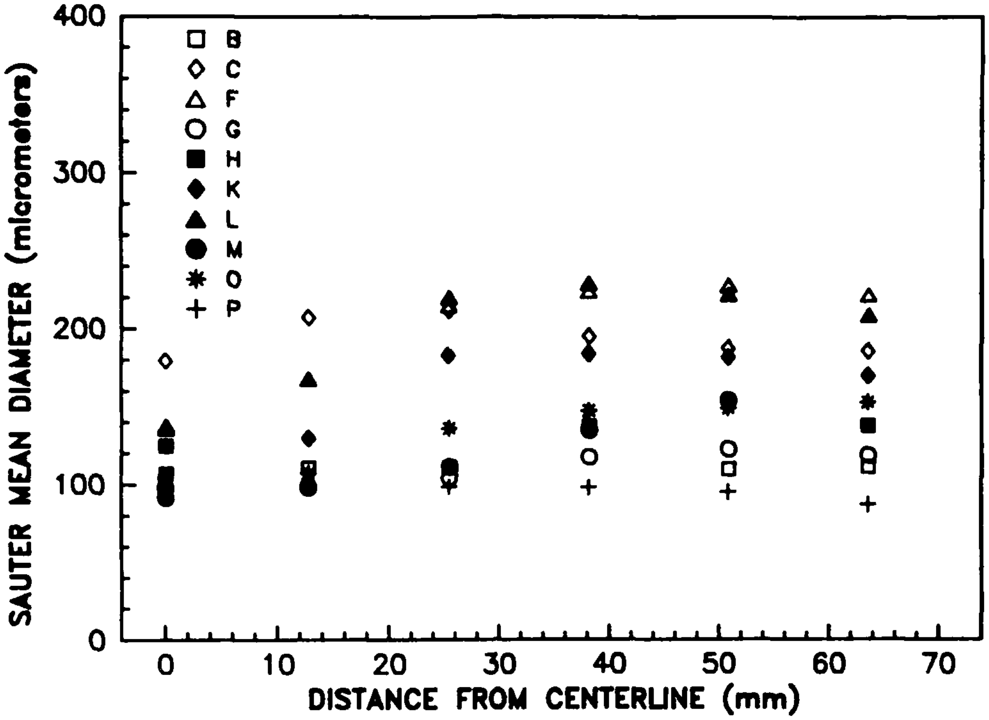

FIGURE 14. SMD DATA FOR ALL INSTRUMENTS, DELAVAN AT 276 kPa

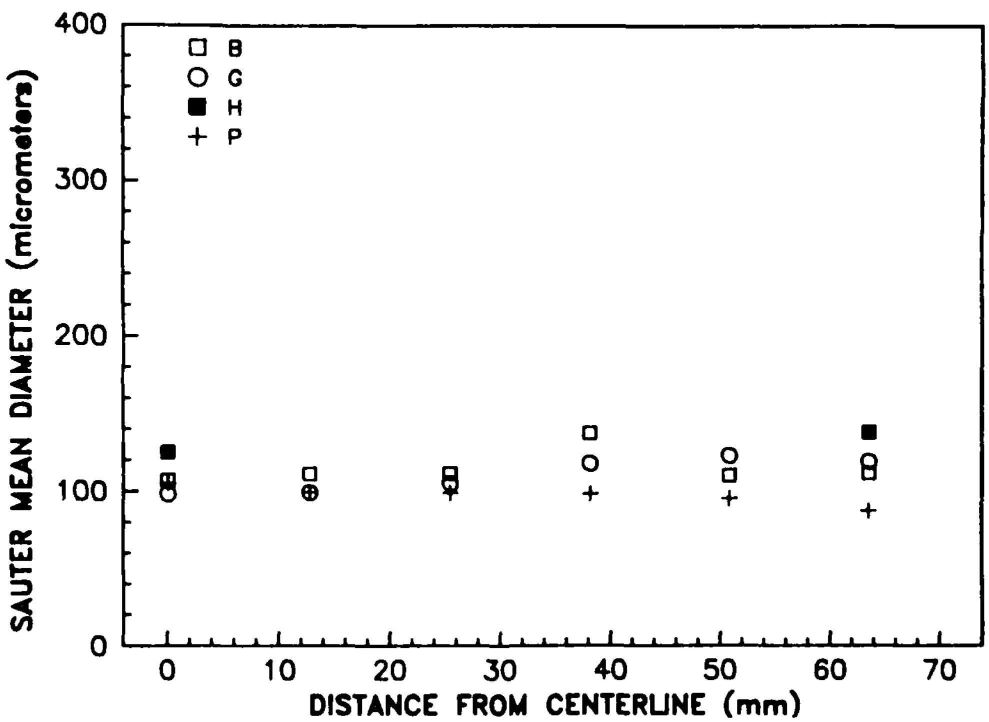

FIGURE 15. MALVERN LINE-OF-SIGHT SMD DATA, DELAVAN AT 276 kPa

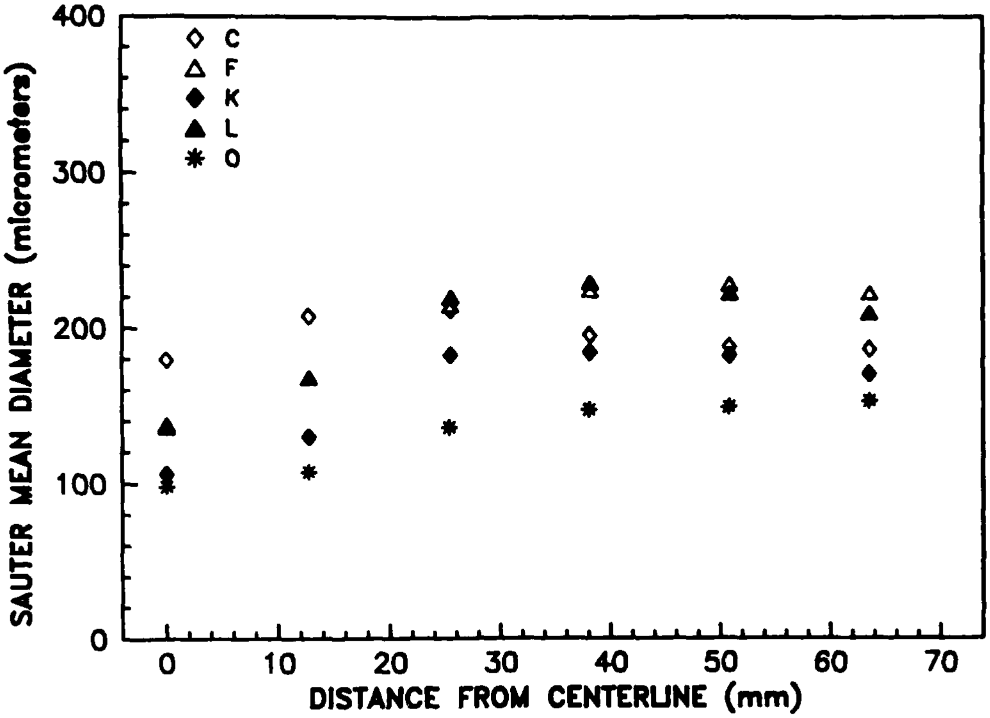

FIGURE 16. TEMPORAL (OR FLUX-SENSITIVE) SMD DATA, DELAVAN AT 276 kPa

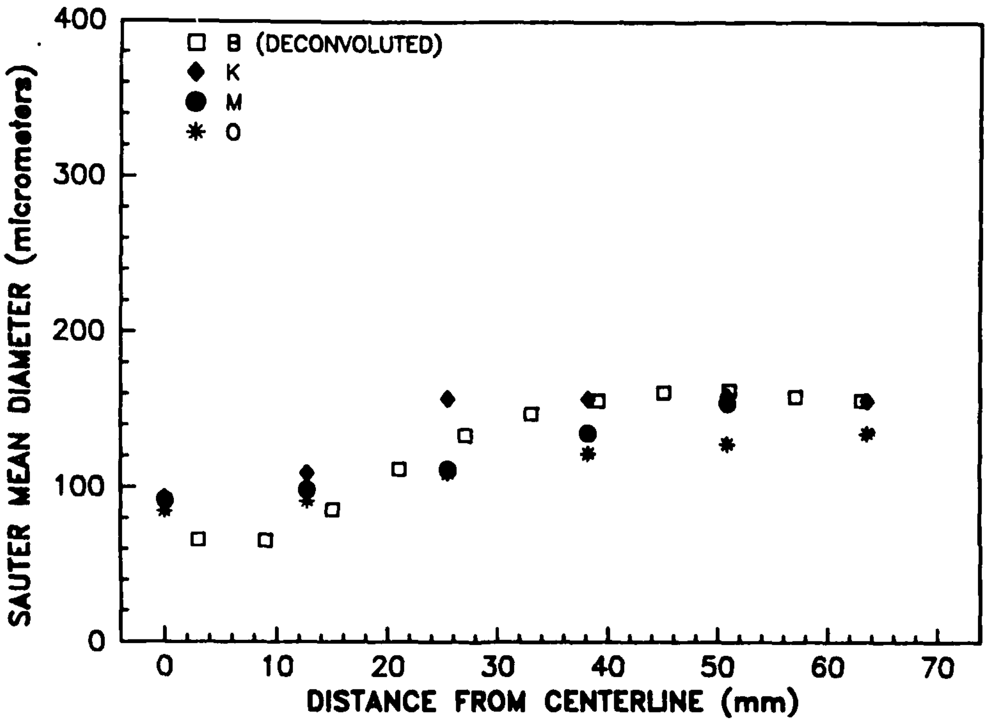

FIGURE 17. SPATIAL (OR CONCENTRATION-SENSITIVE) POINT SMD DATA, DELAVAN AT 276 kPa

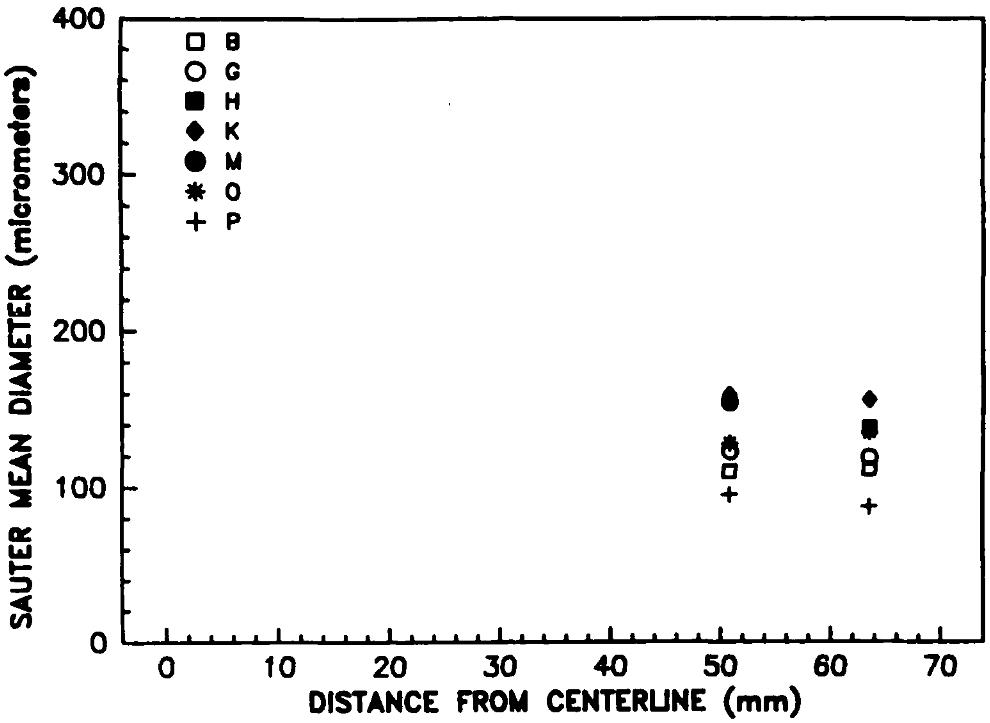

FIGURE 18. SPATIAL SMD DATA AT EDGE OF SPRAY, DELAVAN AT 276 kPa

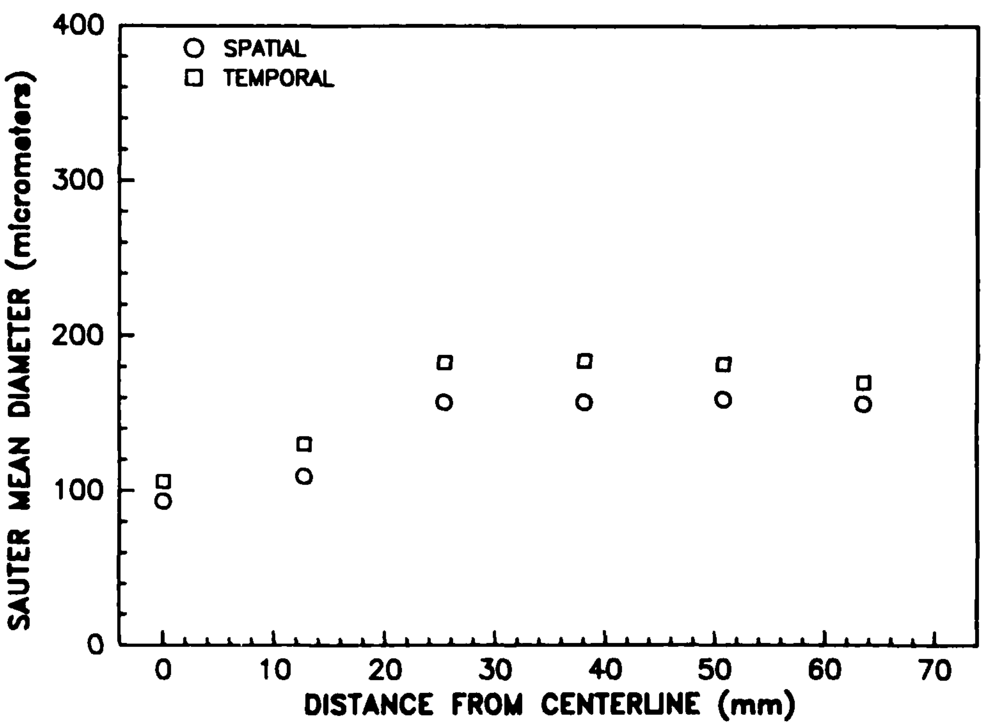

FIGURE 19. TEMPORAL VERSUS SPATIAL SMD DATA (AEROMETRICS), DELAVAN AT 276 kPa

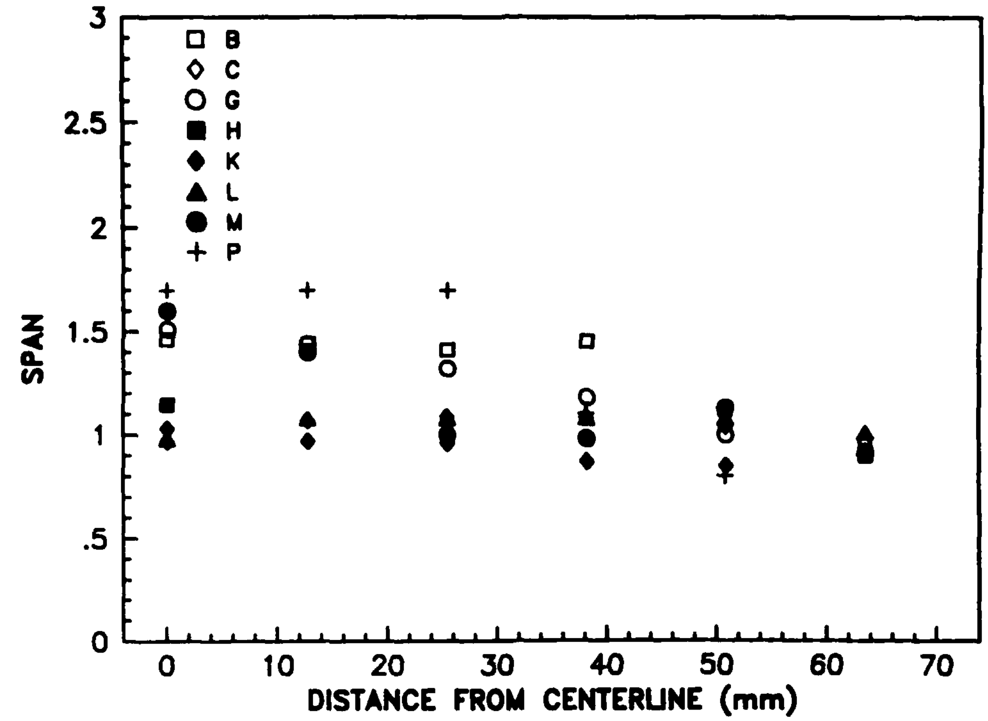

FIGURE 20. SPAN DATA FOR ALL INSTRUMENTS, DELAVAN AT 276 kPa

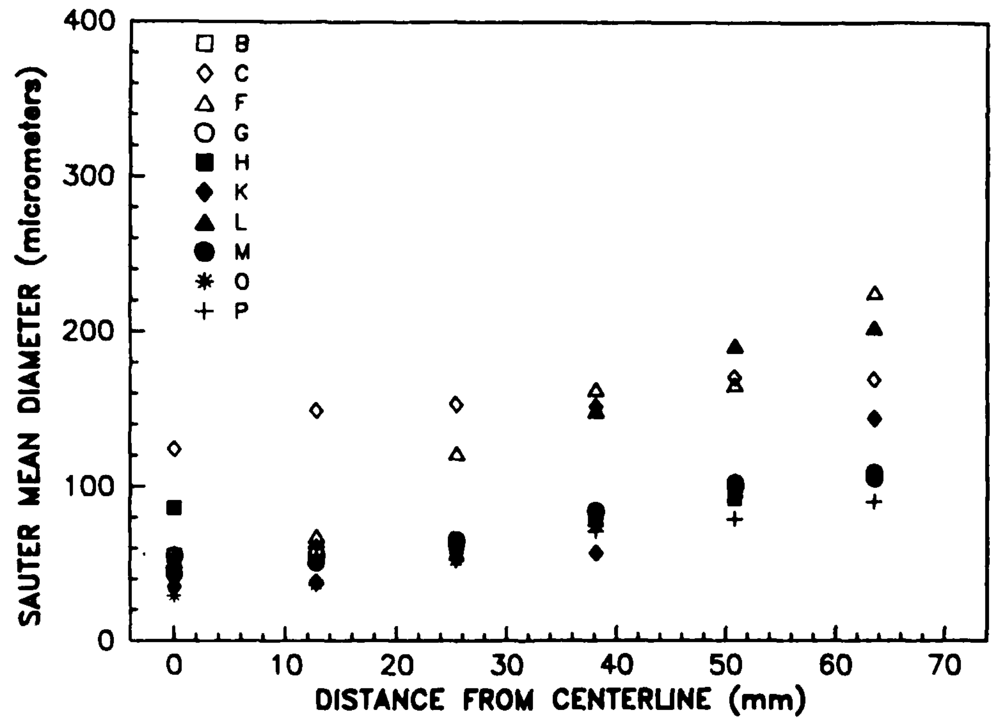

FIGURE 21. SMD DATA FOR ALL INSTRUMENTS, DELAVAN AT 689 kPa

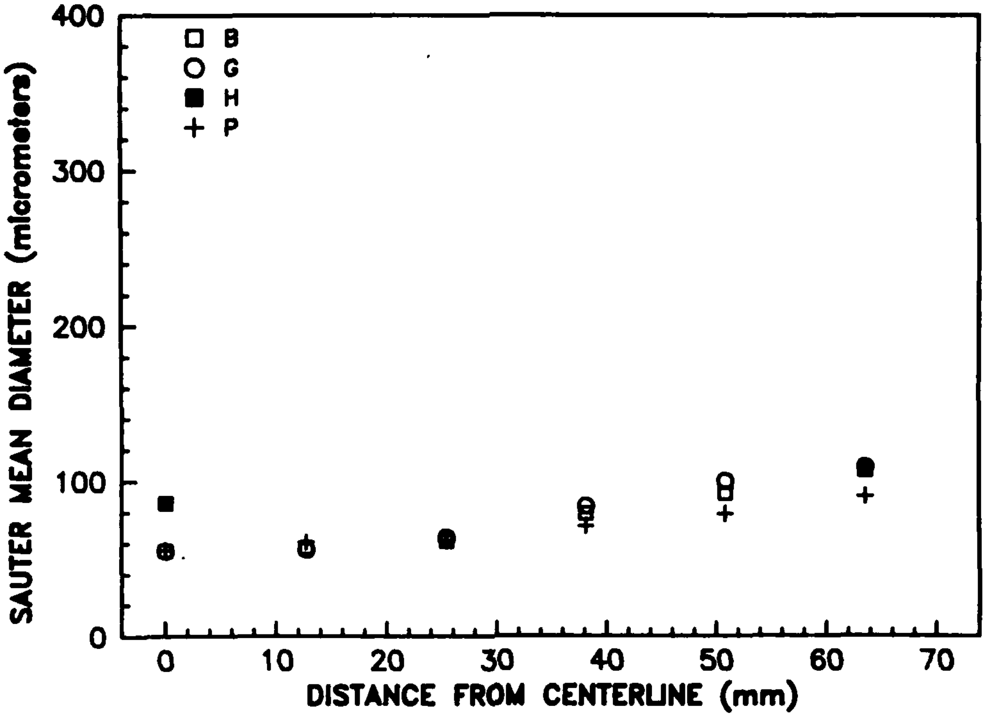

FIGURE 22. MALVERN LINE-OF-SIGHT SMD DATA, DELAVAN AT 689 kPa

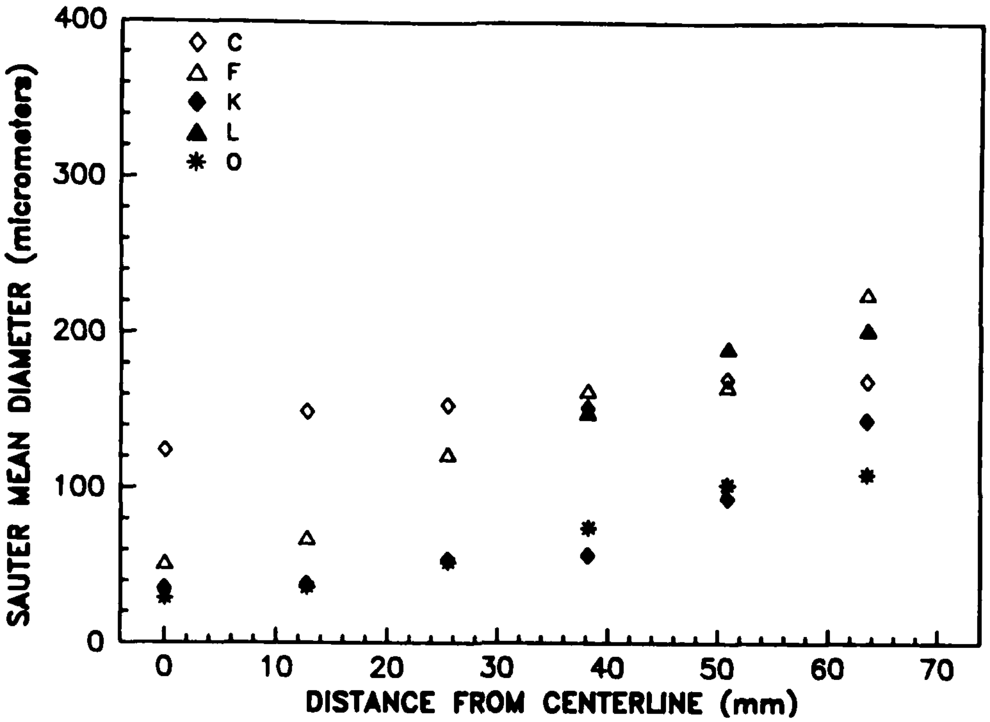

FIGURE 23. TEMPORAL (OR FLUX-SENSITIVE) SMD DATA, DELAVAN AT 689 kPa

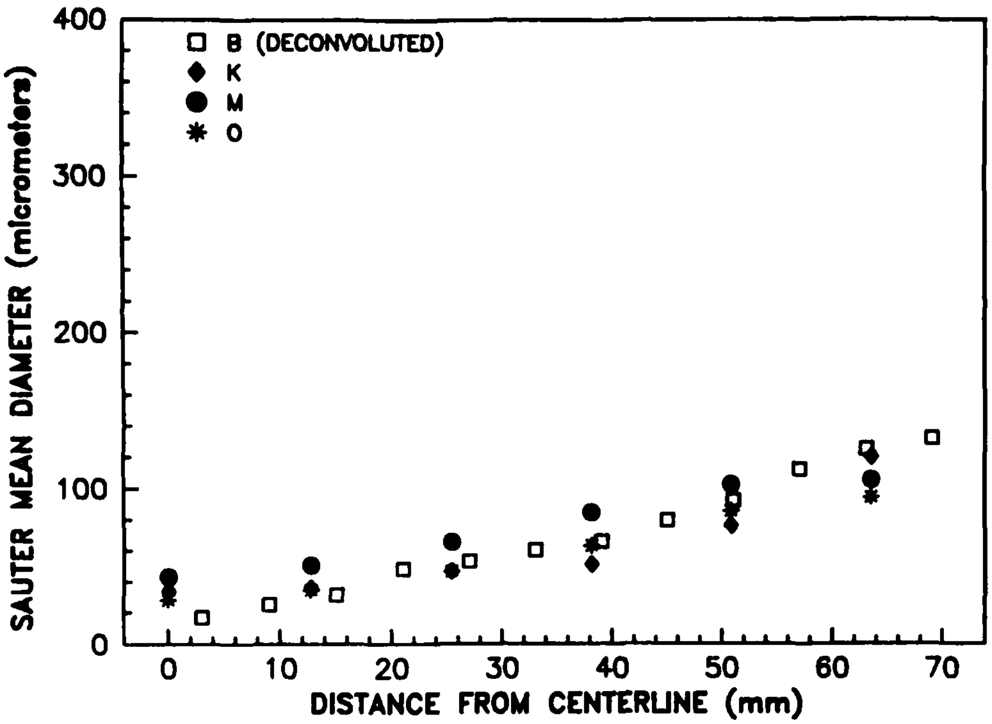

FIGURE 24. SPATIAL (OR CONCENTRATION-SENSITIVE) POINT SMD DATA, DELAVAN AT 689 kPa

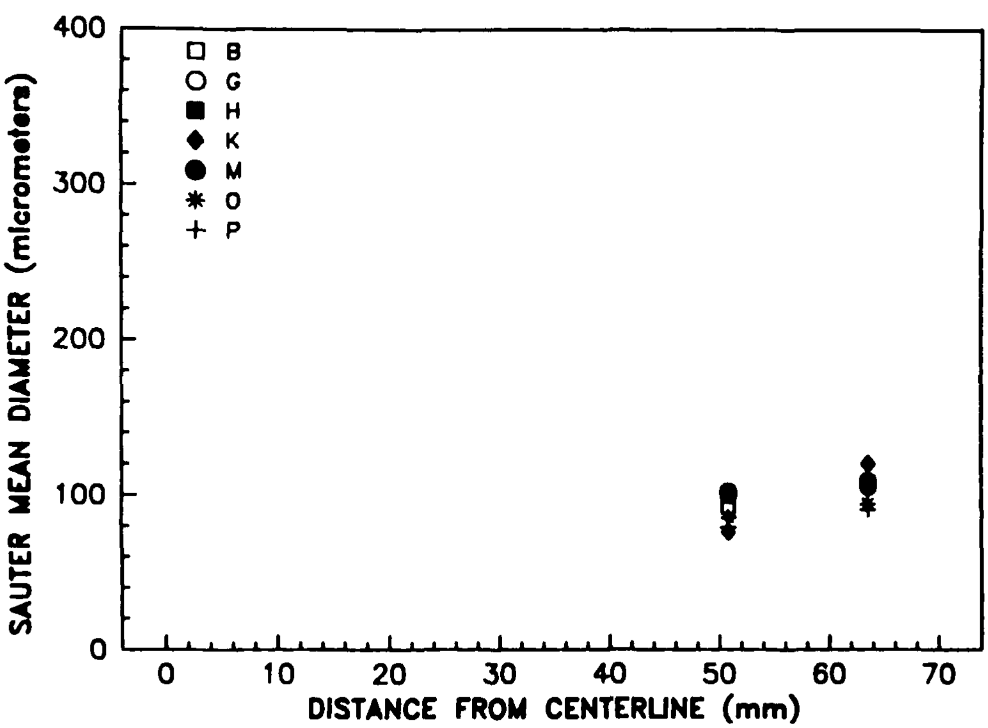

FIGURE 25. SPATIAL SMD DATA AT EDGE OF SPRAY, DELAVAN AT 689 kPa

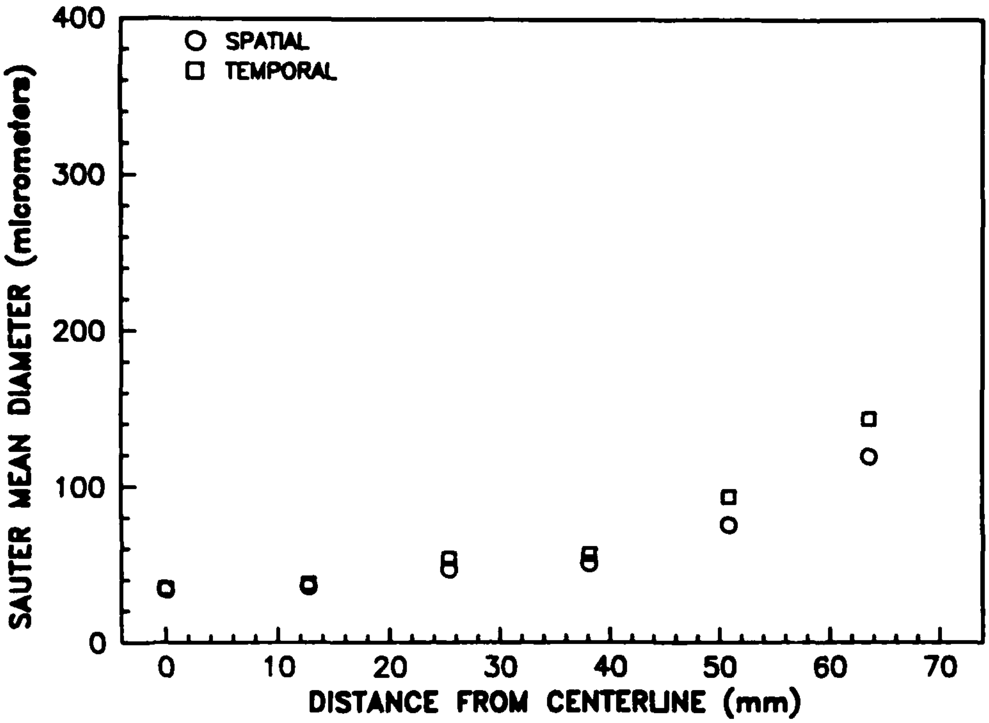

FIGURE 26. TEMPORAL VERSUS SPATIAL SMD DATA (AEROMETRICS), DELAVAN AT 689 kPa

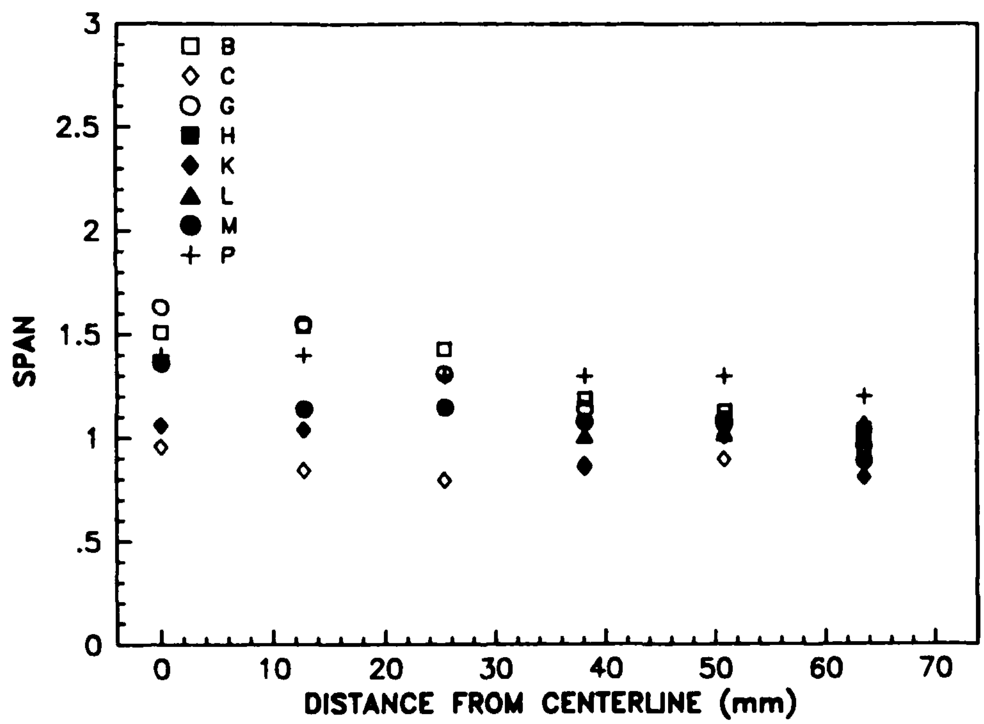

FIGURE 27. SPAN DATA FOR ALL INSTRUMENTS, DELAVAN AT 689 kPa

APPENDIX A

MEASUREMENTS OF SMD AND RELATIVE SPAN FOR ALL PARTICIPATING LABORATORIES

APPENDIX A

MEASUREMENTS OF SMD AND RELATIVE SPAN FOR ALL PARTICIPATING LABORATORIES

A. Data for Parker-Hannifin (P/H) atomizer at pressure differential of 345 kPa

Laboratory	Spatial line-of-sight data: Distance from Centerline (mm)	SMD (μm)	Relative Span
A	0.0	36.9	1.24
	6.3	36.8	1.21
	12.7	40.2	1.02
	19.0	44.2	.88
	25.4	50.2	.81
	31.7	55.7	.72
	38.1	63.6	.64
	44.4	72.6	.55
B	0.0	36.1	1.32
	6.3	32.4	1.30
	12.7	38.3	1.07
	19.0	45.9	.81
	25.4	53.7	.71
	31.7	64.1	.62
	38.1	74.8	.60
	44.4	81.0	.54
D	0.0	37.3	1.27
	6.3	38.1	1.21
	12.7	40.3	1.05
	19.0	45.9	.81
	25.4	54.9	.70
	31.7	62.6	.63
	38.1	75.1	.61
	44.4	84.0	.37
E	0.0	34.7	1.00
	6.3	36.3	1.00
	12.7	39.0	.96
	19.0	44.5	.91
	25.4	52.0	.85

A. Data for Parker-Hannifin (P/H) atomizer at pressure differential of 345 kPa (Cont.)

Spatial line-of-sight data

Laboratory	Distance from Centerline (mm)	SMD (μm)	Relative Span
E (Cont.)	31.7	62.2	.74
	38.1	72.1	.62
	44.4	78.5	.36
J	0.0	40	
	6.3	44	
	12.7	49	
	19.0	54	
	25.4	61	
	31.7	67	
	38.1	73	
	44.4	79	
P	0.0	33.5	1.3
	6.3	38.0	1.3
	12.7	39.1	1.1
	19.0	51.6	0.9
	25.4	59.8	0.8
	31.7	60.9	0.9
	38.1	68.9	1.0
	44.4	57.5	1.2

Spatial "point" data

Laboratory	Distance from Centerline (mm)	SMD (μm)	Relative Span
B (Deconvoluted)	2.0	15.5	
	6.0	18.0	
	10.0	19.3	
	14.0	21.9	
	18.0	27.4	
	22.0	36.7	
	26.0	45.0	
	30.0	53.6	
	34.0	66.1	
	38.0	80.4	
	42.0	87.8	
	46.0	88.7	

A. Data for Parker-Hannifin (P/H) atomizer at pressure differential of 345 kPa (Cont.)

Spatial "point" data (Cont.)

Laboratory	Distance from Centerline (mm)	SMD (μm)	Relative Span
Q	0.0	24.4	.99
	4.0	24.4	.95
	8.0	26.8	1.00
	12.0	30.7	.91
	16.0	35.2	1.02
	20.0	40.1	.79
	24.0	46.7	.79
	28.0	57.1	.78
	32.0	68.3	.74
	36.0	81.3	.66
	40.0	91.7	.63
	44.0	98.3	.58

Temporal "point" data

Laboratory	Distance from Centerline (mm)	SMD (μm)	Relative Span
C	0.0	44.6	1.04
	6.3	44.1	1.04
	12.7	80.2	1.25
	19.0	105.1	1.05
	25.4	112.6	.97
	31.7	145.3	.78
	38.1	157.9	.79
	44.4	166.7	.76
N	0.0	14.6	
	6.3	13.4	
	12.7	20.3	
	19.0	28.5	
	25.4	37.2	
	31.7	54.2	
	38.1	72.4	
	44.4	79.1	
	50.8	83.7	
	57.1	84.5	
	63.5	85.3	

A. Data for Parker-Hannifin (P/H) atomizer at pressure differential of 345 kPa (Cont.)

Temporal "point" data

Laboratory	Distance from Centerline (mm)	SMD (μ m)	Relative Span
Q	0.0	24.2	.99
	4.0	24.2	.95
	8.0	26.7	1.00
	12.0	30.8	.91
	16.0	35.7	1.02
	20.0	41.4	.79
	24.0	49.0	.79
	28.0	61.1	.78
	32.0	74.5	.74
	36.0	88.2	.66
	40.0	97.9	.63
	44.0	103.1	.58

B. Data for Parker-Hannifin (P/H) atomizer at differential pressure of 689 kPa

Spatial line-of-sight data

Laboratory	Distance from Centerline (mm)	SMD (μ m)	Relative Span
A	0.0	28.0	1.30
	6.3	30.3	1.13
	12.7	34.0	.94
	19.0	38.7	.83
	25.4	44.4	.71
	31.7	51.5	.63
	38.1	62.2	.57
	44.4	72.0	.50
B	0.0	25.3	1.47
	6.3	27.2	1.25
	12.7	33.9	.91
	19.0	38.9	.75
	25.4	46.3	.66
	31.7	55.9	.57
	38.1	69.4	.52
	44.4	78.1	.33

B. Data for Parker-Hannifin (P/H) atomizer at differential pressure of 689 kPa (Cont.)

Spatial line-of-sight data

Laboratory	Distance from Centerline (mm)	SMD (μm)	Relative Span
D	0.0	28.7	1.37
	6.3	29.2	1.30
	12.7	31.7	1.07
	19.0	37.2	.84
	25.4	44.5	.71
	31.7	52.6	.64
	38.1	65.5	.57
	44.4	77.5	.33
E	0.0	26.7	1.00
	6.3	28.1	1.00
	12.7	30.5	.96
	19.0	36.4	.91
	25.4	43.4	.85
	31.7	54.7	.74
	38.1	66.1	.62
	44.4	74.0	.36
I	0.0	51.3	
	6.3	52.2	
	12.7	53.2	
	19.0	53.6	
	25.4	55.4	
	31.7	60.1	
	38.1	67.8	
	44.4	79.8	
J	0.0	31	
	6.3	35	
	12.7	42	
	19.0	46	
	25.4	53	
	31.7	58	
	38.1	70	
	44.4	77	

B. Data for Parker-Hannifin (P/H) atomizer at differential pressure of 689 kPa (Cont.)

Spatial line-of-sight data

Laboratory	Distance from Centerline (mm)	SMD (μm)	Relative Span
P	0.0	26.4	1.5
	6.3	27.0	1.4
	12.7	29.1	1.2
	19.0	32.8	1.0
	25.4	38.9	.9
	31.7	47.7	.9
	38.1	49.5	1.3
	44.4	36.8	1.4

Spatial "point" data

Laboratory	Distance from Centerline (mm)	SMD (μm)	Relative Span
B (Deconvoluted)	2.0	11.3	
	6.0	13.3	
	10.0	16.1	
	14.0	20.8	
	18.0	25.8	
	22.0	29.9	
	26.0	38.6	
	30.0	46.7	
	34.0	52.6	
	38.0	59.2	
	42.0	70.4	
	46.0	75.0	
Q	0.0	12.1	.84
	4.0	13.6	1.16
	8.0	19.9	.72
	12.0	25.5	.55
	16.0	30.1	.44
	20.0	33.5	.44
	24.0	39.1	.41
	28.0	45.1	.48
	32.0	55.2	.61
	36.0	69.7	.89
	40.0	77.8	.68
	44.0	80.8	.59

B. Data for Parker-Hannifin (P/H) atomizer at differential pressure of 689 kPa (Cont.)

Temporal "point" data

Laboratory	Distance from Centerline (mm)	SMD (μm)	Relative Span
C	0.0	50.9	1.19
	6.3	50.8	1.39
	12.7	73.4	1.36
	19.0	104.9	1.20
	25.4	112.6	1.13
	31.7	155.6	.80
	38.1	175.0	.82
	44.4	186.4	.73
F	0.0	8.1	
	6.3	8.5	
	12.7	11.1	
	19.0	15.7	
	25.4	21.4	
	31.7	40.8	
	38.1	64.3	
	44.4	66.4	
N	0.0	11.4	
	6.3	12.3	
	12.7	19.9	
	19.0	26.4	
	25.4	34.8	
	31.7	44.0	
	38.1	65.6	
	44.4	78.4	
	50.8	79.4	
	57.1	74.3	
Q	0.0	11.9	.84
	4.0	13.5	1.16
	8.0	19.7	.72
	12.0	25.5	.55
	16.0	30.2	.44
	20.0	33.9	.44
	24.0	40.0	.41
	28.0	46.8	.48
	32.0	58.3	.61
	36.0	73.1	.89
	40.0	81.3	.68
	44.0	83.4	.59

C. Data for Delavan atomizer at differential pressure of 276 kPa

Spatial line-of-sight data

Laboratory	Distance from Centerline (mm)	SMD (μm)	Relative Span
B	0.0	106.9	1.46
	12.7	111.0	1.44
	25.4	111.4	1.41
	38.1	137.5	1.45
	50.8	110.1	1.12
	63.5	111.6	.91
G	0.0	98	1.51
	12.7	99	1.44
	25.4	105	1.32
	38.1	118	1.18
	50.8	123	1.00
	63.5	119	.91
H	0.0	125	1.14
	63.5	138	.90
P	0.0	105.0	1.7
	12.7	99.0	1.7
	25.4	98.9	1.7
	38.1	98.3	1.1
	50.8	95.2	.8
	63.5	87.2	.9

Spatial "point" data

Laboratory	Distance from Centerline (mm)	SMD (μm)	Relative Span
B (Deconvoluted)	3.0	65.9	
	9.0	65.3	
	15.0	85.3	
	21.0	111.7	
	27.0	133.5	
	33.0	147.4	
	39.0	156.0	
	45.0	161.2	
	51.0	162.8	
	57.0	158.6	
	63.0	156.2	

C. Data for Delavan atomizer at differential pressure of 276 kPa (Cont.)

Spatial "point" data

Laboratory	Distance from Centerline (mm)	SMD (μ m)	Relative Span
K	0.0	93	1.03
	12.7	109	.97
	25.4	157	.96
	38.1	157	.87
	50.8	159	.85
	63.5	156	.92
M	0.0	91.6	1.60
	12.7	98.2	1.40
	25.4	111.7	1.00
	38.1	135.0	.98
	50.8	154.2	1.13
O	0.0	84.5	
	12.7	91.0	
	25.4	109.2	
	38.1	122.1	
	50.8	128.2	
	63.5	135.0	

Temporal "point" data

Laboratory	Distance from Centerline (mm)	SMD (μ m)	Relative Span
C	0.0	179.5	.96
	12.7	207.5	1.07
	25.4	211.9	1.08
	38.1	195.1	1.08
	50.8	187.7	1.04
	63.5	185.8	.96
F	0.0	138	
	12.7	168	
	25.4	215	
	38.1	224	
	50.8	228	
	63.5	222	

C. Data for Delavan atomizer at differential pressure of 276 kPa (Cont.)

Temporal "point" data (Cont.)

Laboratory	Distance from Centerline (mm)	SMD (μm)	Relative Span
K	0.0	106	
	12.7	130	
	25.4	183	
	38.1	184	
	50.8	182	
	63.5	170	
L	0.0	136	
	12.7	168	
	25.4	220	
	38.1	229	
	50.8	222	
	63.5	209	
O	0.0	98.1	
	12.7	107.4	
	25.4	136.3	
	38.1	147.3	
	50.8	149.1	
	63.5	152.8	

D. Data for Delavan atomizer at differential pressure of 689 kPa

Spatial line-of-sight data

Laboratory	Distance from Centerline (mm)	SMD (μm)	Relative Span
B	0.0	55.2	1.51
	12.7	57.3	1.54
	25.4	61.3	1.43
	38.1	79.2	1.19
	50.8	92.1	1.13
	63.5	107.7	1.04

D. Data for Delavan atomizer at differential pressure of 689 kPa

Spatial line-of-sight data

Laboratory	Distance from Centerline (mm)	SMD (μm)	Relative Span
G	0.0	55	1.63
	12.7	56	1.55
	25.4	64	1.31
	38.1	84	1.14
	50.8	100	1.09
	63.5	109	.96
H	0.0	86	1.36
	63.5	107	.99
P	0.0	55.8	1.4
	12.7	60.9	1.4
	25.4	62.0	1.3
	38.1	71.3	1.3
	50.8	79.1	1.3
	63.5	90.3	1.2

Spatial "point" data

Laboratory	Distance from Centerline (mm)	SMD (μm)	Relative Span
B (Deconvoluted)	3.0	17.1	
	9.0	25.5	
	15.0	31.6	
	21.0	48.3	
	27.0	53.3	
	33.0	60.5	
	39.0	65.9	
	45.0	79.6	
	51.0	92.1	
	57.0	112.0	
	63.0	125.3	
	69.0	132.0	
	75.0	133.5	
	81.0	132.0	

D. Data for Delavan atomizer at differential pressure of 689 kPa (Cont.)

Spatial "point" data (Cont.)

Laboratory	Distance from Centerline (mm)	SMD (μ m)	Relative Span
K	0.0	34	
	12.7	36	
	25.4	47	
	38.1	51	
	50.8	76	
	63.5	120	
M	0.0	43.0	1.36
	12.7	50.4	1.14
	25.4	65.6	1.15
	38.1	84.3	1.08
	50.8	102.1	1.07
	63.5	105.1	.89
O	0.0	28.1	
	12.7	34.5	
	25.4	46.7	
	38.1	63.0	
	50.8	85.4	
	63.5	93.9	

Temporal "point" data

Laboratory	Distance from Centerline (mm)	SMD (μ m)	Relative Span
C	0.0	123.9	.95
	12.7	148.9	.84
	25.4	153.3	.79
	38.1	151.6	.85
	50.8	170.4	.89
	63.5	169.1	.92
F	0.0	51.5	
	12.7	67.7	
	25.4	122.0	
	38.1	163.0	
	50.8	166.0	
	63.5	226.0	

D. Data for Delavan atomizer at differential pressure of 689 kPa (Cont.)

Temporal "point" data

Laboratory	Distance from Centerline (mm)	SMD (μ m)	Relative Span
K	0.0	35.	
	12.7	38.	
	25.4	54.	
	38.1	57.	
	50.8	94.	
	63.5	144.	
L	38.1	149.0	1.01
	50.8	191.0	1.02
	63.5	203.0	1.07
O	0.0	29.0	
	12.7	36.2	
	25.4	36.2	
	38.1	75.0	
	50.8	102.9	
	63.5	109.4	

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